8

Illustrated World of Science Encyclopedia

Astronomy I:
THE MOON, THE
PLANETS AND
THE SUN

THE WORLD OF SCIENCE

THE MOON—Satellite of the Earth.

THE WORLD OF SCIENCE

VOLUME
8
ASTRONOMY I

The Moon, the Planets, and the Sun

with

The Illustrated Science Dictionary

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CHICAGO

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VOLUME 8

ASTRONOMY I

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INTRODUCTION

Volume 8 of The World of Science is primarily concerned with the solar system. While there is no doubt that space technology has revolutionized solar system astronomy, most of what astronomers know about the sun and the planets has been learned through patient analysis of data obtained from earthbound instruments. The astronomer is thus handicapped by not being able to examine his subject firsthand; instead, he must be content to interpret experiments already performed by nature. Much of the material in this volume explains how astronomers are able to overcome this handicap and determine, for example, the rotation rate of cloud-covered Venus or the temperature within a sunspot.

Six articles describe the topology of the moon and discuss the probable origin of craters and maria on this celestial neighbor. In addition there is at least one article on each major planet. Discussed for each planet is important physical data such as size, mass, and satellites. New discoveries such as the nonsynchronous rotation of Mercury and the radio emission from Jupiter are included. Planetary subjects of particular interest, such as the rings of Saturn and life on Mars, have separate articles devoted to them.

In many ways the sun is the most interesting and important object in the solar system. Astronomers study the sun not only because it is so important to life on Earth but also because it presents the only opportunity to study a star close up. Because the sun is the only normal star for which astronomers can investigate prominences, sunspots, and magnetic fields, understanding the sun becomes crucial to understanding the other stars. In this volume articles on the sun explore the phenomena just mentioned plus the solar spectrum, the sun as a radio source, eclipses of the sun, and the sun's magnetic field.

Besides the sun and the planets, the solar system contains numerous small bodies including comets, asteroids, and meteors. Although insignificant in mass compared with the sun and major planets, these objects are important for several different reasons. Fallen meteors (meteorites) are valuable samples of extraterrestrial material, and laboratory analysis of these rocks provides clues to the history of the solar system. Comets are often spectacular; they are also of great interest because the motions in their tails reveal something of the physical conditions in interplanetary space. Furthermore, when an asteroid or comet passes near a major planet, the mass of the planet can be computed from its effect on the orbit of the smaller body. This volume contains five articles on asteroids, comets, and meteors; these articles give a careful description of the objects and also consider the relationships of the three. For example, some periodic meteor showers are due to the passage of the Earth through the orbits of old comets that have long since disappeared.

Finally, two articles on celestial objects outside the solar system complete this volume. "Diffuse Nebulas" and "Galaxies" describe the various kinds of objects that have a nebulous or cloudy appearance when seen through the telescope. They range from dust clouds that shine by reflected starlight (such as the nebulosity of the Pleiades) to the external galaxies that are vast star systems sometimes resembling the Milky Way (such as the Andromeda Nebula), and include such mysterious objects as the Crab Nebula. This nebula receives special attention because of recent discoveries about its nature. It has long been known that this nebulosity is the result of a supernova explosion that occurred A.D. 1054. Interest was further aroused when it was discovered that the Crab Nebula is a strong source of both radio waves and x-rays. The latest surprise has been the identification of the central star of the nebula (undoubtedly the object left over after the explosion) as one of a class of pulsating radio sources known as pulsars. If this star is really a neutron star, as many believe, the Crab Nebula becomes extremely important for understanding the final stages of stellar evolution.

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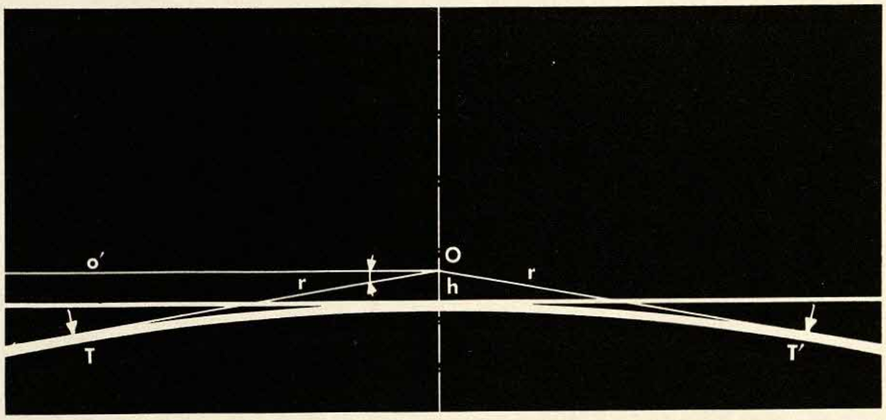
THE CELESTIAL SPHERE AND ITS MOTION | appearance and reality

Celestial phenomena and the positions of heavenly bodies may best be described by imagining that they are all placed on a transparent sphere—an inverted "bowl" which is concentric with the terrestrial sphere, or Earth. Since the human eye, from its observation point on Earth, is unable to determine the different distances of these celestial bodies, it is only natural to imagine such a hypothetical sphere.

A more basic reason for the concept of a celestial sphere is that this hypothetical geometric figure is extremely useful for determining the position—that is, the direction of the line of sight—of a star. The line may be defined as the straight line that runs from the observer's eye to the celestial body being observed. The inclination of the line of sight may vary with respect to the horizon, and it may have any direction with respect to the cardinal points (north, east, south, west). To illustrate this, imagine the observer at the center of a sphere, with his lines of sight intersecting the sphere. The line of sight may also be related to the plane of the horizon and to the cardinal points. And the point of intersection of the line of sight on the celestial sphere may be considered with reference to other points on the sphere.

1



THE THEORETICAL AND REAL HORIZON— The astronomical horizon is described in Illustration 2. Standing in the open, however, an observer can never really see the astronomical horizon, because his vision will always be interrupted by houses, trees, mountains, or even minor undulations of terrain. At sea, the horizon can be seen only if visibility is perfect. The astronomical horizon, however, is defined as a circumference traced on a plane tangent to the Earth's surface at the point at which the observer O is standing. The marine horizon is described as where the tangent points T and T' fall in the field of vision. Therefore, observer O situated at height h on the surface of the sea will see the marine horizon in the direction OT, rather than Oo'. By increasing the height h up to a certain value, the radius of visibility r is increased; the equation is $r = 3.55\sqrt{h}$, where h is expressed in meters and r in kilometers. This formula is generally used for small values of h, but it can also be applied at the heights involved in aerial navigation.

Because the Earth's surface is divided by meridians and parallels, it is quite simple to establish references and determine the position of any particular point on its surface. These divisions are naturally derived from the rotating movement of the Earth, the positions of the poles, and the equatorial plane.

Using the same criteria, the celestial sphere can also be divided. It, too, seems to rotate on its own axis, although this apparent rotation is, of course, simply the reflection of the Earth's rotating motion. Greek scholars thought the stars rose and set because of a daily westward rotation of the sphere around an axis thrust through a globular Earth. Copernicus taught that the Earth's daily rotation set the celestial scenery in motion.

In the study of astronomy, at least four different systems may be employed to determine celestial coordinates. Each is particularly suitable for a specific category of phenomena. These four systems are: (1) the system of altazimuthal coordinates that refer to the horizon, the zenith, and the meridian; (2) the system that relates the positions of the stars to the rotation of the Earth; (3) the system based on the Earth's revolution around the sun, in which the plane of the Earth's orbit or ecliptic is projected on the celestial sphere; and (4) the system based on the galactic equator (the central plane of the Galaxy), which is used to determine the relative positions of bodies both within and without the Galaxy itself.

Three basic considerations apply to the use of each of these systems. One consideration is the reference points and circles that determine the position of a body; that is, its coordinates on the celestial vault. A second consideration is the method of determining the fundamental reference circles. The third consideration is the manner by which the values of the coordinates in a given system can be determined when the values of another system are known.

This article deals in detail only with the first two considerations. The third involves a simple mathematical problem that can be solved through spherical trigonometry.

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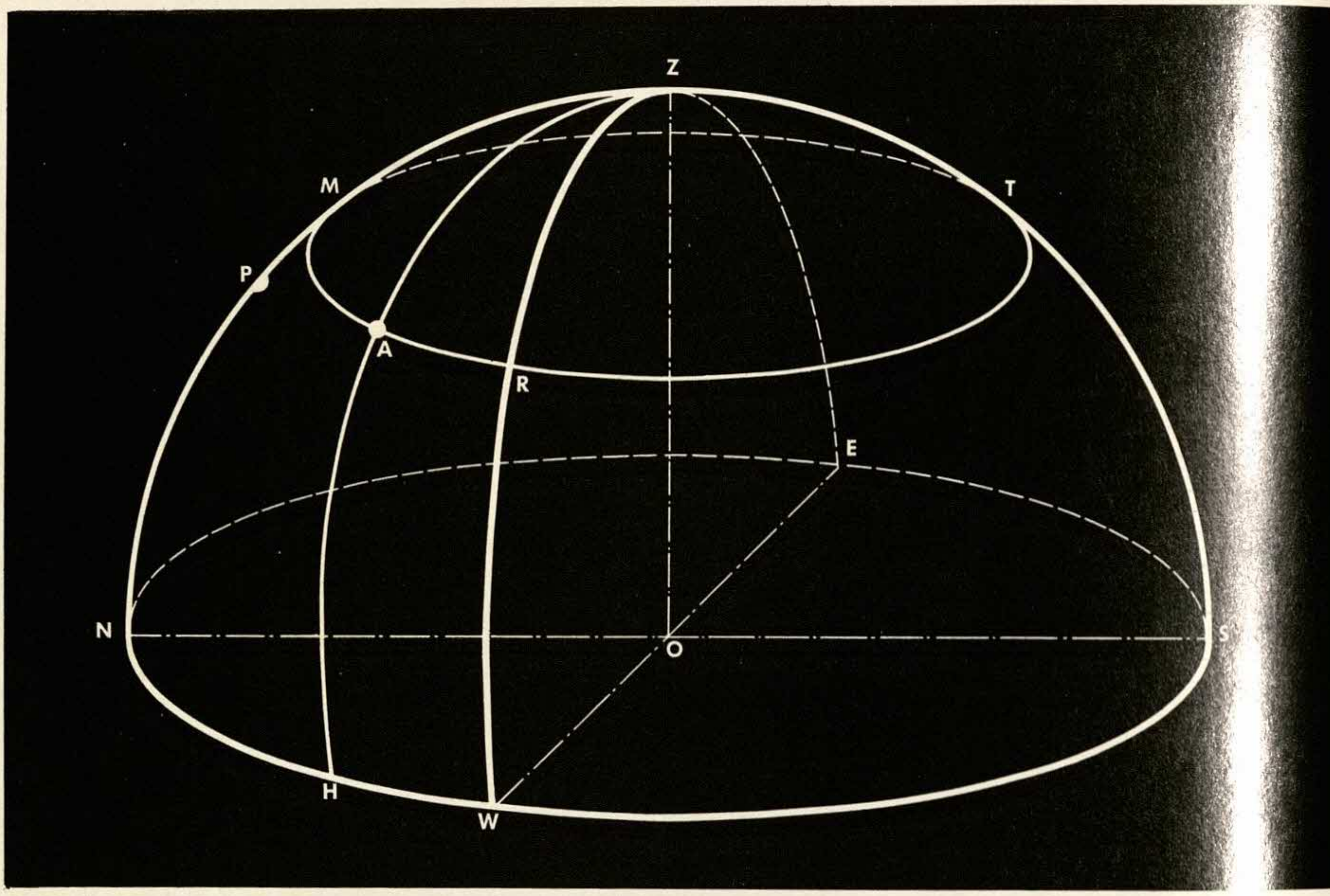

ALTAZIMUTHAL COORDINATES—To understand how the celestial sphere is subdivided by the system of altazimuthal coordinates, imagine that a plumb line is extended from the center of the sphere (always indicated by *O*) toward both the top and the bottom. The intersection of this line with the top of the sphere occurs at a point called the zenith, a name derived from Arabic astronomy of the last centuries of the first millennium. On the celestial sphere, the zenith is indicated as *Z; ZO* is the direction of the plumb line.

The point where the plumb line would meet the celestial sphere at the bottom is called the nadir (another Arabic name), indicated by *N.* It does not appear on the hemisphere shown here simply because only the top half of the celestial sphere is illustrated—that part appearing above the circle *SENW*, representing the astronomical horizon on which are noted the cardinal points.

The diameter of the sphere is unimportant, since the systems of coordinates do not depend on this factor. *A* marks the meeting point of the observer's line of sight with a celestial object on the sphere. The following procedure describes the position of this object on the celestial sphere: from the zenith, circles *ZS, ZE, ZN, ZW* are traced to meet the horizon perpendicularly at each of the cardinal points. A fifth circle *ZAH* is traced through *A.* These circles are called vertical circles, or circles of altitude. The two fundamental circles are *NZS* (the meridian circle) and *EZW* (the first vertical).

The angle of the arc *AH* measured in degrees is the altitude of the celestial object on the horizon. The angle can be determined by joining points *A* and *O*, and points *H* and *O*. The complementary arc *ZA* is the zenith distance of the body.

The circles that divide the celestial sphere by passing through the zenith and the nadir are great circles—those with diameters equal to that of the celestial sphere. For a complete description of the celestial sphere, horizontal circles must also be traced. An example is the horizontal plane (parallel to the plane of the horizon) that passes through the representative point *A.* This horizontal circle *MRT*, like all others parallel to it or the equator, is called the almucantar, still another Arabic name.

The horizontal circles give one coordinate —the altitude—of a celestial body. All bodies falling on the same horizontal circle are at the same altitude. Before considering the second coordinate of the altazimuthal system, the azimuth, note that the meridian circle, which passes through the zenith *Z* and intersects the horizon at cardinal points *N* and *S* (north and south), also passes through the celestial pole *P.* Also, the first vertical is the circle perpendicular to the meridian and meets the horizon at the cardinal points *E* and *W* (east and west).

All the elements needed to define the azimuth of body *A* are now present. The azimuth is the plane angle that the line of sight must turn through in moving from the south cardinal direction to the point *H*, which is the point of intersection of circle *ZAH* with the horizon. Or, imagine a plane tangent to the celestial sphere at *Z*, and project on it, from *O*, the meridian and the altitude circle *ZAH;* the size of the resulting plane angle is used to define that of the angle on the celestial sphere of the circles *SZ* and *ZH*). The azimuth may also be expressed as the arc *SWH.*

Astronomers often calculate azimuth in the direction *SWNE*, beginning from the south. Navigators, however, measure from the north, in the direction NESW, and many astronomers are now adopting this convention.

The two coordinates used in this system are altitude and azimuth, hence the name altazimuth coordinates. These coordinates are a good starting point toward an understanding of the other systems of coordinates.

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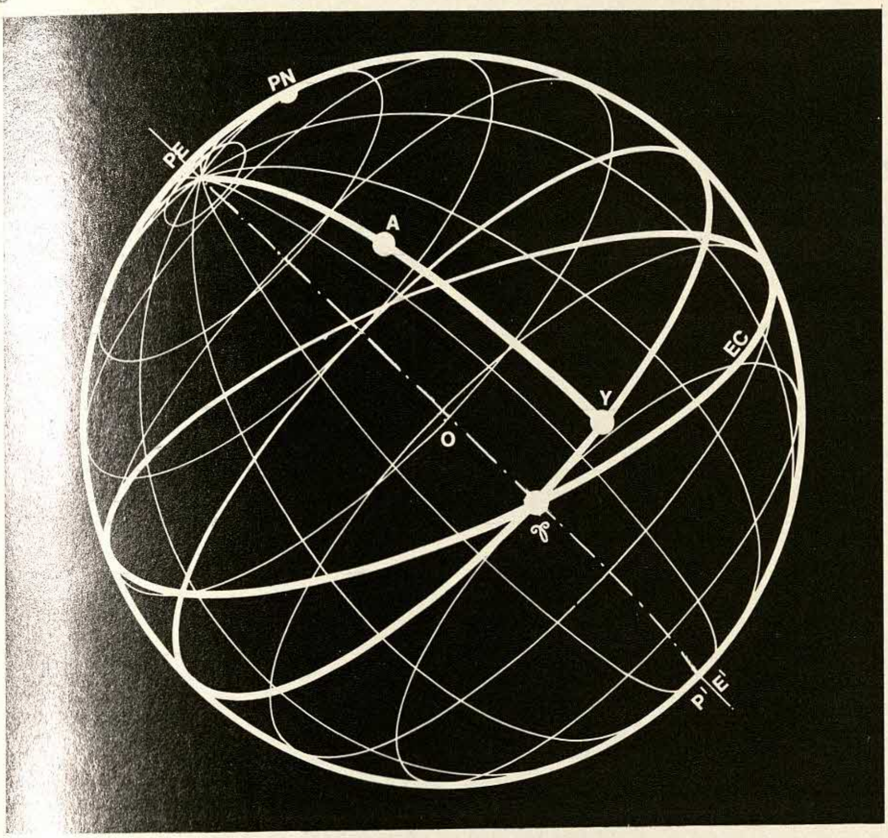

CELESTIAL LATITUDE AND LONGITUDE—Using equations that contain coordinates of the bodies themselves, the apparent movement of the sun on the ecliptic and of the moon and planets on planes near to that of the ecliptic is studied, described, and predicted by astronomers. In this way developed a system of coordinates having the ecliptic as a great circle of reference. The illustration shows the celestial sphere divided by the circle of the ecliptic; the ecliptic in turn determines the position on the celestial sphere of two poles, *PE* and *P′E′*. The ecliptic circle is inclined approximately 23° 27′ to the celestial equator *EC*. Hence, the arc *PNPE* is also 23° 27′.

The position of star *A* can be described as follows: A great circle, passing through the poles of the ecliptic and the star, is traced, and the arc *YA*, called the latitude of the star, is measured. A second great circle, passing through the poles of the ecliptic and the vernal point ♈, is traced; the angle ♈ *PEY* is called the longitude of the star. This system of coordinates is particularly useful in describing the motion of the planets.

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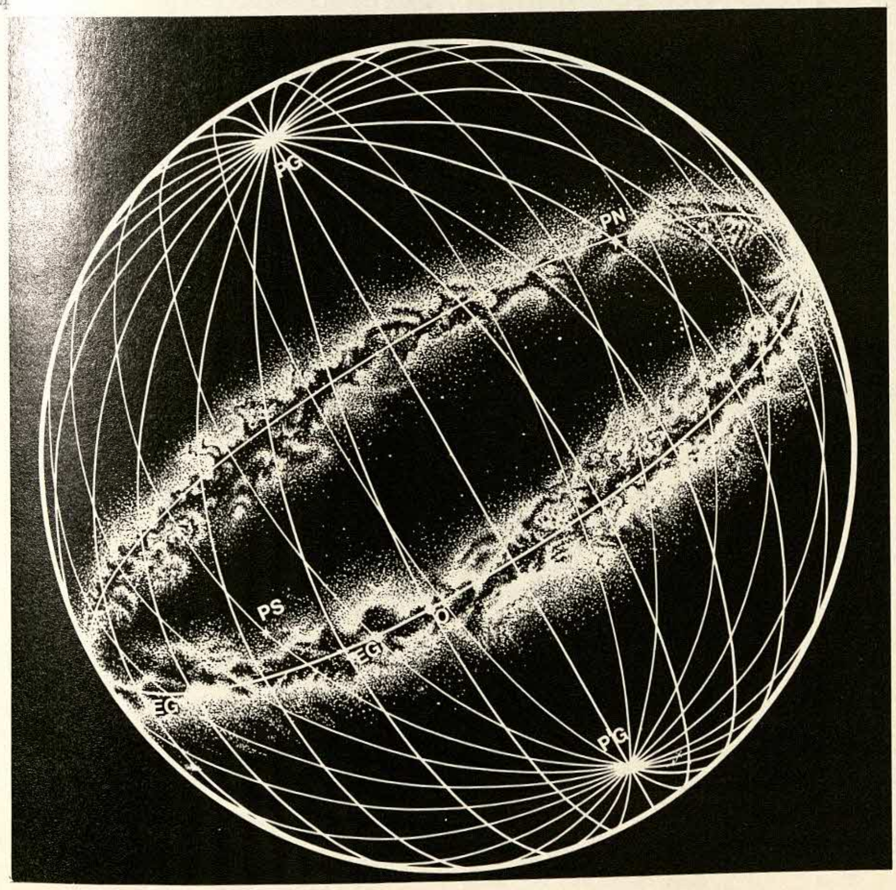
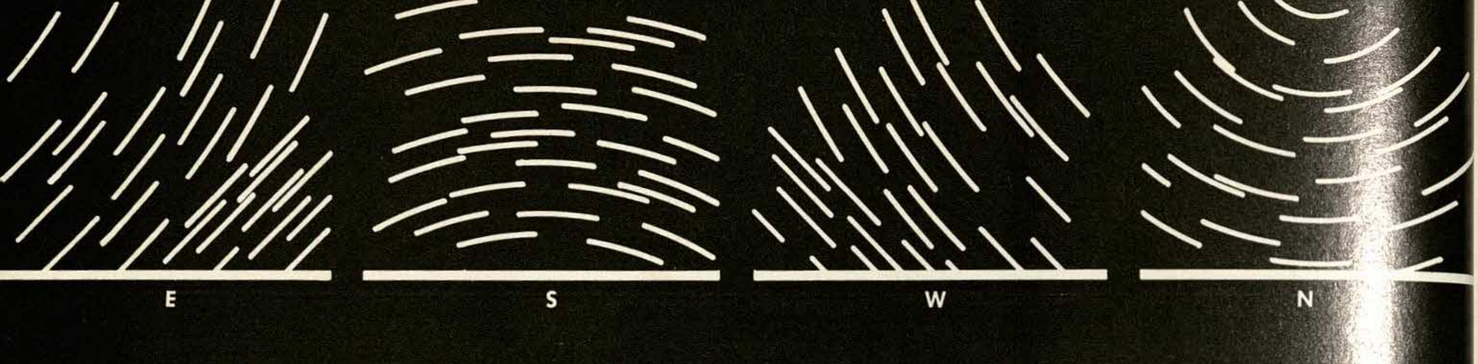


THE GALACTIC COORDINATES—When studying the structure of the galactic system, it is convenient to use coordinates based on the particular symmetries of the system itself. This illustration shows the celestial sphere, on which the Milky Way has been traced. Along its axis runs the galactic equator, which, in turn, determines the positions of the respective poles. Because of the uncertain nature of the composition of the Milky Way, it is not possible to pinpoint precisely the position of bodies with this system. The celestial equatorial coordinates of the galactic poles (*PG*, *P′G*) are approximately 12*h* 40*m* right ascension and 28° north declination.

The origin of the galactic coordinates is chosen to be a point in the constellation Sagittarius, at a right ascension of 17*h* 43*m* and a declination of −29°. This origin was chosen because radio and optical data indicate that this is the direction to the center of the galaxy.

Describing the position of a conspicuous family of celestial objects by means of galactic coordinates indicates whether the objects tend to become noticeably more dense toward the galactic equator. If they do, it is possible that they are part of the galactic system itself. If, on the other hand, they are outside the system, their coordinates will appear to be distributed in the proximity of the galactic poles. This is because a layer of absorbing material in the galactic plane prevents observation of extragalactic objects near the plane. *PN* and *PS* are the north and south celestial poles. *EG* is the galactic equator, while *O*, on this equator, is the point from which longitudes are calculated.



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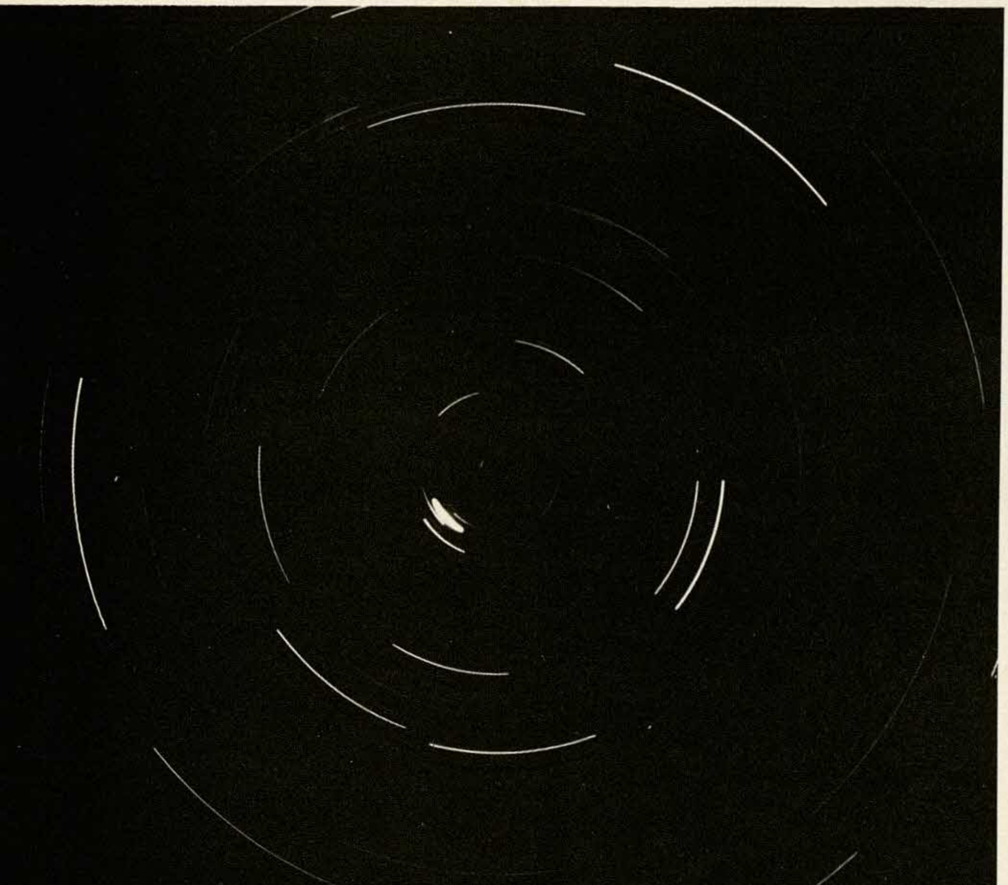


5c

TERRESTRIAL ROTATION AND THE CELESTIAL SPHERE—The Earth's rotation causes an apparent rotation of the celestial sphere. This allows definition of a system of coordinates that is particularly useful in determining the positions of celestial bodies and in following their movements with an equatorial telescope.

To an observer of the celestial sphere who is situated neither too close to the Earth's equator nor to its poles, the stars seem to move in rather different ways (Illustration 5a). In the east, as shown at the left, those stars rising exactly at the cardinal point and at a small area surrounding it seem to move in a straight line. Toward the north in the same picture they seem to move upward in concave circles; to the south, downward in concave circles. In the second diagram (south) the stars move in concave circles toward the bottom.

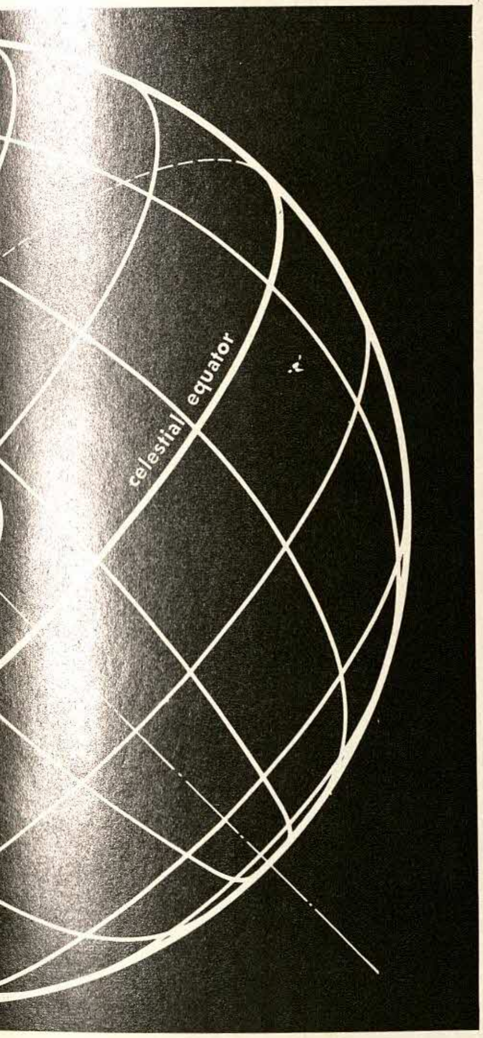
The larger the circles, the higher the stars are on the horizon; all are concentric and their center, which does not appear on the horizon, is the celestial south pole. The third diagram represents the situation to the west, which is symmetrical to that to the east. Finally, from the north, the stars move in concave circles toward the top. The larger the circles, the lower they are on the horizon; all are concentric to the celestial north pole.

This photograph of the celestial pole (Illustration 5b) is a time exposure of two hours. The stars are not luminous points, but rather are in apparent motion, because of the "rotation" of the celestial sphere. It is clearly seen that all of the stars travel through angles of equal size. The star that has left the most intense trace is Polaris, the Pole Star (North Star), the closest to the north pole. Despite its name, its position obviously is not exactly that of the north pole (one of the two fixed points in the rotating motion of the celestial sphere, since it describes a rather large arc around the pole). The position of the Pole Star in relation to the celestial pole varies with time because the latter moves on the sphere due to perturbational action, causing a slow variation in the fundamental planes such as the equator and the ecliptic. Until the year 2105, the present Pole Star will continue to move closer to the pole; then it will move slowly away from it.

The method shown in Illustration 5c can be used to describe the position of any body located on the celestial sphere, using as reference planes great circles that are different from those shown in Illustration 1. While the altazimuthal method is convenient for determining the coordinates of a celestial body by means of an easily used instrument, its drawback is that it must refer to the terrestrial horizon. The second method has the advantage of being independent of this horizon. While a star constantly varies in altitude and azimuth because of the apparent rotation of the celestial sphere, it remains unchanged (for all practical purposes) in relation to the coordinates obtained by this method. As already stated, two points of the celestial sphere—the poles—re-

main perfectly still, regardless of the rotational movement. These are marked *PN* and *PS*, the north celestial pole and the south celestial pole.

If the celestial sphere is intersected by planes that pass through the two poles, a series of great circles is obtained that, for reasons that will become apparent, are called hour circles. The sphere is then intersected by a plane through its center, perpendicular to the junction of the two poles. This plane, called the equator, is a great circle. Other planes, parallel to the equator, are traced on the



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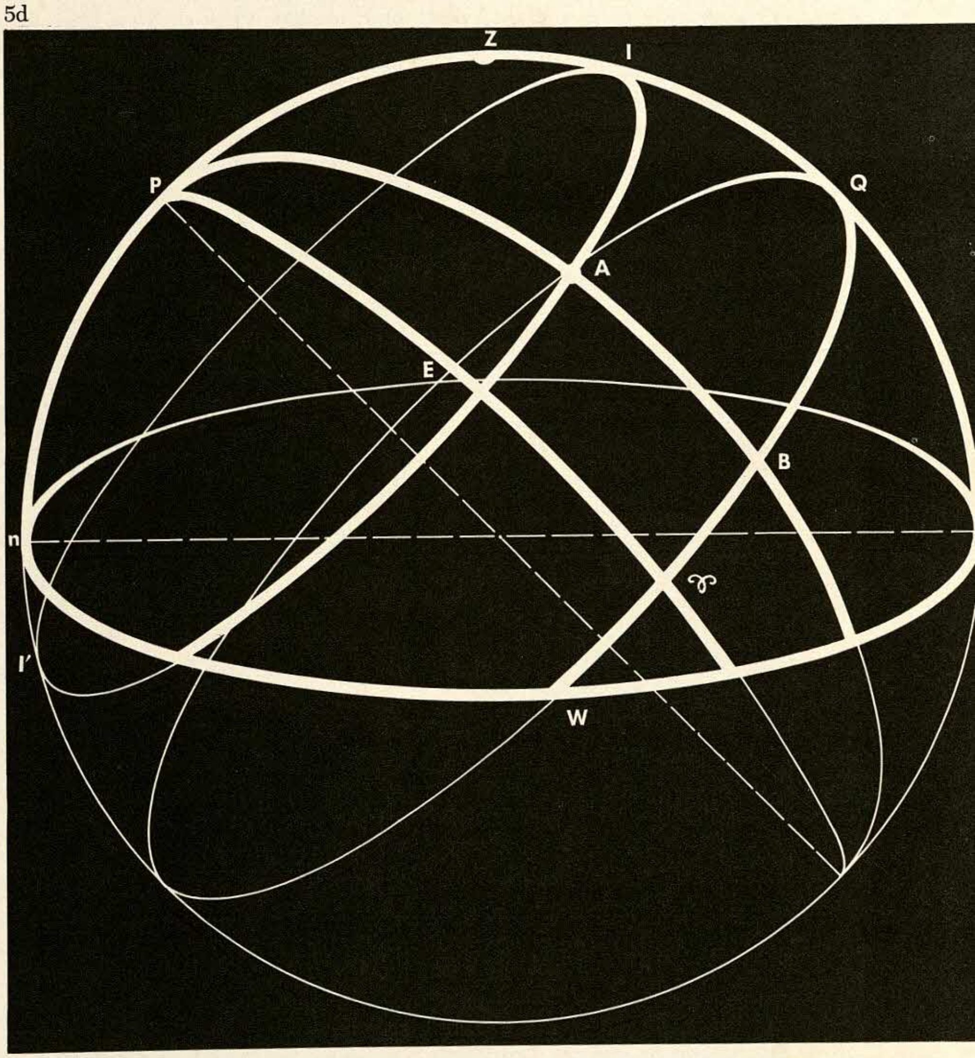


sphere. These are not great circles, but are called parallels of declination. Through every star passes an hour circle that serves to define the position of the star. The hour circle that passes through the zenith coincides with the meridian circle.

Illustration 5d shows a new use of circles for orientation on the celestial sphere. Now look at that part of the celestial sphere that can be observed above the horizon of any point on Earth (the illustration shows a point in the north temperate zone). Note the circles on this portion. *NWSE* is the astronomical horizon with the cardinal points marked. *P* is the pole; *Z* the zenith. *EQW* is the celestial equator, or, more properly, half the equator—the half that is above the horizon. *NPZS* is the meridian, while *A* is any star. The great circle that passes through both this star and the pole is called the hour circle of the star. *BA* is the declination of the star, the arc of the hour circle between the star's position and the celestial equator. *AP* is the polar distance. The circle of declination of the star is indicated by *I*. This also identifies the path along which the star moves due to the rotation of the celestial sphere. Part of this path is above the horizon and part is below it.

Another very important circle must be considered. A point is marked on the celestial equator to act as the origin of the coordinates; it is indicated with a symbol derived from the Greek letter γ, the symbol of the constellation Aries ♈. This point is called the vernal point, and is also referred to as the first point of Aries.

One other important circle is not shown on the celestial sphere. This is the ecliptic, the projection on the celestial sphere of the plane of the Earth's orbit. The ecliptic intersects the celestial equator at two points (diametrically opposite, since the ecliptic too is a great circle). The point that falls in the constellation Aries is the first point of Aries. It is the point corresponding to that which the sun reaches on March 20-21 every year, the vernal equinox. Its opposite point is the autumnal equinox. The great circle of the celestial sphere that passes through the pole and the vernal point is occasionally called the equinoctial colure, and is very important for defining the coordinates of a star. The angle *AP* ♈, or the arc ♈ *B*, measures the right ascension of a given star. The right ascension is calculated as positive, beginning at the vernal point and increasing toward the east. Therefore, the right ascension of a star becomes larger the later that star passes the meridian with respect to the vernal point. Since it is an angle, the right ascension can be measured in degrees and sexagesimal fractions. It is more convenient, however, to measure right ascension in units of time. An astronomer can easily use a chronometer regulated on the hour at which the vernal point passes the meridian. This device indicates the right ascension of a star as the time the star passes the meridian.

The angle *ZPA*, or the arc *QB*, measures the hour angle of the star. The declination of the star and its hour angle precisely define the position of the star on the celestial sphere; they are called hour coordinates. From these two coordinates, it is possible to derive the altazimuthal coordinates. The declination and the right ascension are called equatorial coordinates. The meridian serves as zero of the hour angles; the hour angle of a star situated west of the meridian is indicated as positive, that of a star to the east as negative. The hour angle is normally measured in degrees from 0° to 360°, but it may also be measured in hours, from 0*h* to 24*h*.

THE LENGTH OF A DAY | the astronomical measurement of time

At midday, by definition, the sun should be exactly south (or north, depending upon one's location) above the horizon, at a height depending on the season. However, if an observer waits, watch in hand, until precisely noon and then observes the position of the sun, it is more than likely that the position will be several degrees off from due south (or north), and at a slightly different deviation from day to day. A series of observations will reveal some aspects of the sun's motion and the apparently varying length of the day, from noon to noon, at a given point on Earth. The time interval between successive middays varies throughout the year because the Earth's orbit is elliptical.

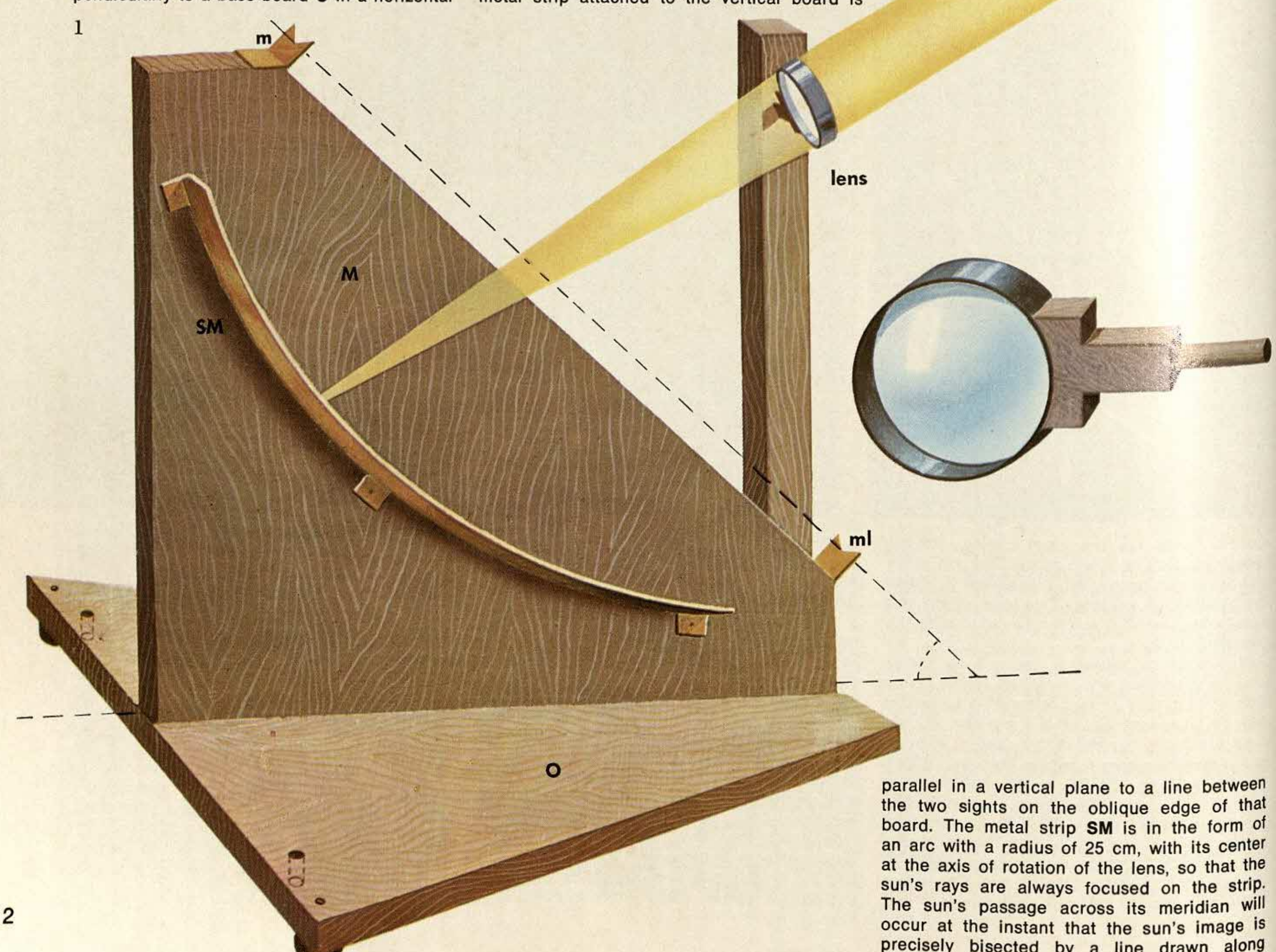
A sundial is a device that measures time according to the movement of the sun. The ancients used a sundial to tell the time of day. They drove a stick at an oblique angle into the ground and marked off lines on the ground at intervals, just where the stick cast a shadow. If these intervals were evenly spaced, the time they represented would not be evenly spaced—and, indeed, the "hours" of the ancients were of uneven length, and one hour would differ from another according to the season.

For the purpose of experiment, all that is needed is an instrument that shows when the sun is due south (or north) from the point of observation. This would not be a complete sundial, but a sundial that shows true midday. To construct such an instrument, the essentials are some wood, a strip of metal and a suitable lens (as shown in Illustration 1).

One of the wooden boards is set perpendicularly to the other; a carpenter's square assures a perfect right angle. The horizontal board may be set on a window sill or any similar support, and is stabilized by three "feet" on the lower surface, of equal length—pieces of hard rubber, or screws of equal length inserted from the

THE MODEL SUNDIAL—A wooden board **M**, with an oblique side cut at an angle so that sights fixed at its extremities **m** and **ml** are aligned on the Pole Star, is attached perpendicularly to a base board **O** in a horizontal position. A lens with a focal length of 25 cm (about 10 in.) is set into a vertical post alongside the vertical board so that a line between the center of the lens and the middle of a metal strip attached to the vertical board is parallel in a vertical plane to a line between the two sights on the oblique edge of that board. The metal strip **SM** is in the form of an arc with a radius of 25 cm, with its center at the axis of rotation of the lens, so that the sun's rays are always focused on the strip. The sun's passage across its meridian will occur at the instant that the sun's image is precisely bisected by a line drawn along the center of the strip.

1



upper surface. The vertical board must have one side evenly cut at an angle that will be sighted against the Pole Star. At the upper and lower ends of this side are fixed metal sights, like those used on rifles —they may be shaped with either shears or a saw—and carefully mounted in alignment with the plane of the board. Alongside the vertical board, also mounted perpendicularly to the horizontal board, is a firmly mounted stick through which a hole is drilled; the handle of the lens is inserted into this hole. The purpose of the handle is to rotate the lens so that the light from the sun will follow the precise center of an arc of metal attached to the side of the vertical board.

This metal arc must have a radius of curvature of about 25 cm (about 10 in.), and its center of curvature must be opposite the lens held in the upright stick, so that the beam from the sun will always focus on the strip—higher in the winter (when the sun is lower in the sky), and lower in the summer.

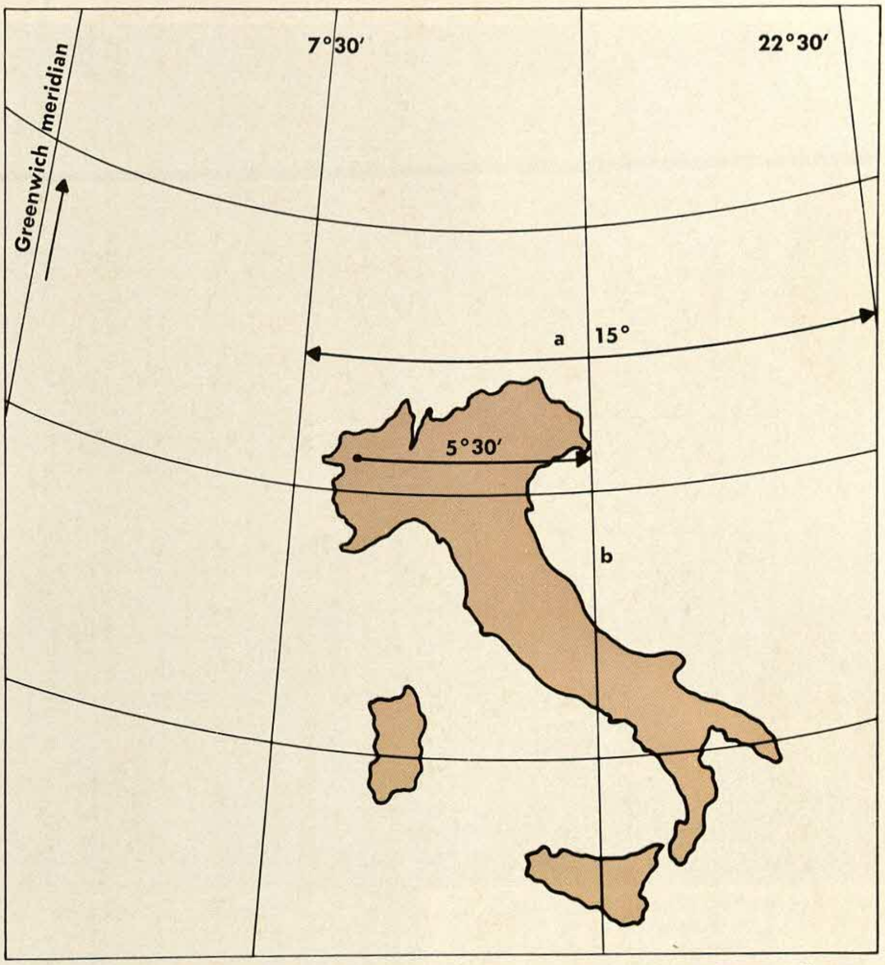
The lens, which is secured in the holder (as illustrated in the detail drawing) by a band of heavy paper or wood, should be an eyeglass lens of +4 diopters, that is, with a focal length of 25 cm (about 10 in.); it can be made by any oculist using a blank of about 15 mm. The lens must not be any larger, for a larger lens would produce an image of the sun so bright that accurate observation would be difficult. When the lens holder is inserted in the upright stick, it should be turned so that the beam of light from the sun will pass through the center of the lens to the center of the metal strip on a line that is in a vertical plane exactly parallel to the plane of a straight line between the two sights.

It is also useful to make two holes in the horizontal wooden board so that the instrument can easily be realigned; thus it can be removed and replaced without the necessity of aligning it with the plane of the meridian each time.

HOW MIDDAY IS OBSERVED

In order to determine the instant of midday, the instrument must be set so that the vertical board is in the plane of the meridian; and in order to do this, a sighting must be taken at night, turning the instrument so that the Pole Star appears along the line of sight parallel to the side of the board that has been cut at an angle. The angle at which the board is cut depends entirely on the latitude of the place of observation, for the angular altitude of the Pole Star at meridian approximately corresponds to the latitude of the point from which it is observed. However, inasmuch as the Pole Star is not precisely at the celestial pole, it is necessary to take a fix on the star at an interval of six hours (which is possible only in spring, autumn, and winter), and to adopt the average of the two fixes as the meridian. This method provides a more accurate determination than the use of a compass, which would require an up-to-date table giving the magnetic declination of the time and place.

2



THE TIME ZONE OF ITALY—This illustration shows an outline of Italy within its time zone **a** of 15°, beginning with longitude 7°30′ east of Greenwich (the longitude shown at the extreme left), with its center **b** at 15° east of Greenwich, and ending at 22°30′ east of Greenwich (the longitude shown at the extreme right). Although the longitude of 15° determines the time for all of Italy, it is obvious that the sun will reach its meridian later at the location in the west shown to be 5°30′ west of the central longitude.

THE MEASUREMENT OF TIME

Once the instrument has thus been properly oriented on a true north-south line, the next step is to wait for the sun to reach its highest elevation above the horizon, at which point it will be due south and the time will be midday. When this happens, its beam will pass through the lens and the sun's image will be divided exactly in half by the line drawn along the middle of the metal strip.

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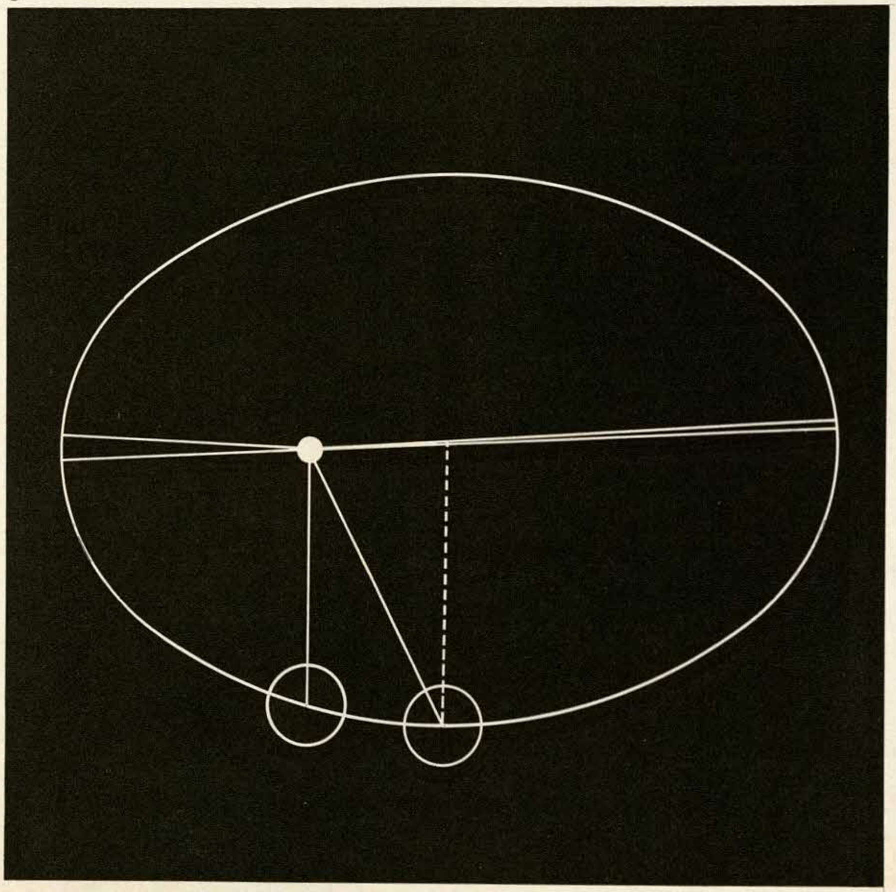


THE EARTH'S ELLIPTICAL ORBIT—Because the Earth, as it rotates around its own axis, also revolves around the sun, the time interval between successive middays is not always the same. The time required for the Earth to make one complete rotation around its axis is known as a sidereal day. The time required to bring the same point of observation on Earth to face the sun in its meridian is known as the solar day, and is somewhat longer. The difference between the sidereal day and the solar day, however, varies throughout the year, because the Earth's orbit is elliptical, as shown.

To determine the instant of time at which this happens, a clock is needed. Although it need not be a precision chronometer, it should have a stop second hand. The clock should be started at an hourly radio signal several hours before midday, and the time noted. When the sun crosses the meridian, the time shown on the watch should again be noted; and another record should be kept of the time shown by the watch at a later hourly radio signal. These observations will reveal any inaccuracy in the clock and make it possible to determine the precise time at which the sun reached its meridian. However, for reasons yet to be explained, this kind of observation can be made only on four specific days during the year.

THE HOUR IS NOT ALWAYS WHAT IT SEEMS

In many countries, for reasons of convenience or economy, the official time is shifted—either during the summer or throughout the year—by one or two hours in advance of solar time. Thus, on that day during the summer when there are 16 hours of daylight, where solar time continues in use, daylight begins at 4:00 in the morning and ends at 8:00 at night, and the sun reaches its meridian at midday; but if the time has been advanced by an hour, daylight begins at 5:00 in the morning (according to the clock) and ends at 9:00 at night—thereby making it usable to more of the population, and the sun reaches its meridian at 1:00 o'clock in the afternoon (which is true solar midday). This must be taken into account when determining the time of the meridian.

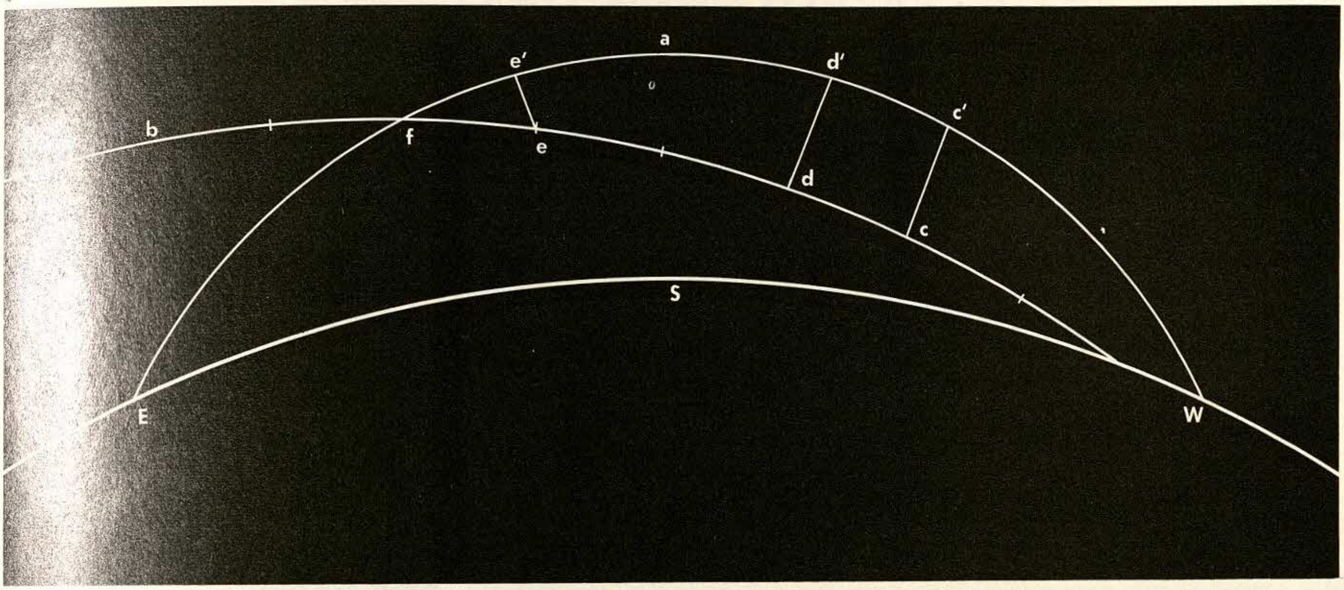
Even more fundamental is the recognition of the division of the world into recognized standard time zones. In general, the 360° of longitude (180° east and 180° west of Greenwich) have been divided into 24 (the number of hours in the day), so that each hour is identified with 15° of longitude. In other words, the meridians are 15° apart; or each time zone is 15° wide. Although solar midday does not actually occur at the same instant throughout a time zone, it is convenient to assign to the entire zone the time of the solar midday in the center of the zone, and to change an entire hour when passing from one zone to another.

Chicago, for example, is in a time zone that extends from 82°30′ to 97°30′ west of Greenwich, with its center at 90° west of Greenwich. When the sun reaches its meridian at the longitude of 90° west, therefore, it is noon, not only along that longitude, but everywhere in the central time zone. Now, at a town located 5°30′ west of the central longitude, the sun will reach its meridian somewhat later—actually, 21 minutes and 57 seconds later. (If it takes the sun 1 hour to cross the entire 15°, it takes 5.5/15 or 0.366 hour or 21 minutes 57 seconds to cross 5½°.) Nevertheless, according to the clock, noon had already arrived at this town almost 22 minutes before the solar midday.

THE EARTH'S ELLIPTICAL ORBIT

The Earth revolves around the sun, not in a circle, but in an elliptical orbit. When it is closest to the sun—at perihelion—it moves with greater speed than when it is farthest from the sun—at aphelion. Therefore, the actual time interval between two successive middays depends not only on the time needed for the Earth's rotation on its axis, but also to some extent on the time consumed in its arc in orbit around the sun; and this is a variable time. In other words, from a point of observation on Earth, the sun returns to its meridian only after the Earth has made slightly more than one complete rotation; the extent of this added

4



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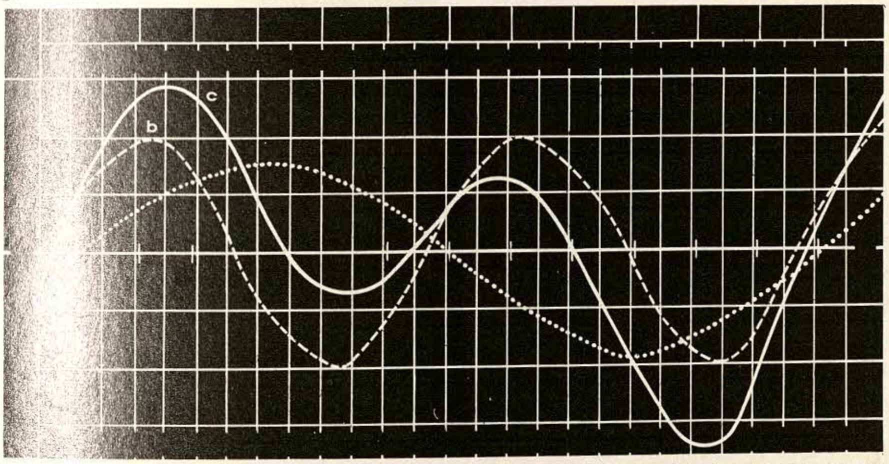


THE EQUATION OF TIME—Combining the effect of the ellipticity of the Earth's orbit (curve **a**) and the effect of the inclination of the plane of the ecliptic to that of the equatorial equator (curve **b**), it is possible to determine the amount by which the revolution of the Earth around the sun is out of phase with the rotation of the Earth on its axis, independently of its position with respect to the sun. The resulting advances or delays, called the equation of time, are represented by curve **c**.

PROJECTION OF THE ECLIPTIC ON THE CELESTIAL EQUATOR—The celestial equator is an imaginary extension into space of the Earth's equator, and is the path followed by the sun (as viewed from Earth) only on the dates of the vernal and autumnal equinoxes; this path is represented by arc **a**. However, the great circle followed apparently in its annual course in the celestial sphere, as viewed from the Earth, is the ecliptic, which has the same plane as the Earth's orbit (a difference resulting from the tilt of the Earth's axis). The ecliptic is represented by arc **b**. The projections of the celestial equator and the ecliptic vary with the seasons. The length of the sun's path along the ecliptic from December to January **cd** does coincide with its path along the celestial equator **c′d′** during those months; but in March its path along the ecliptic **ef** is not the same length as that along the celestial equator **e′f**.

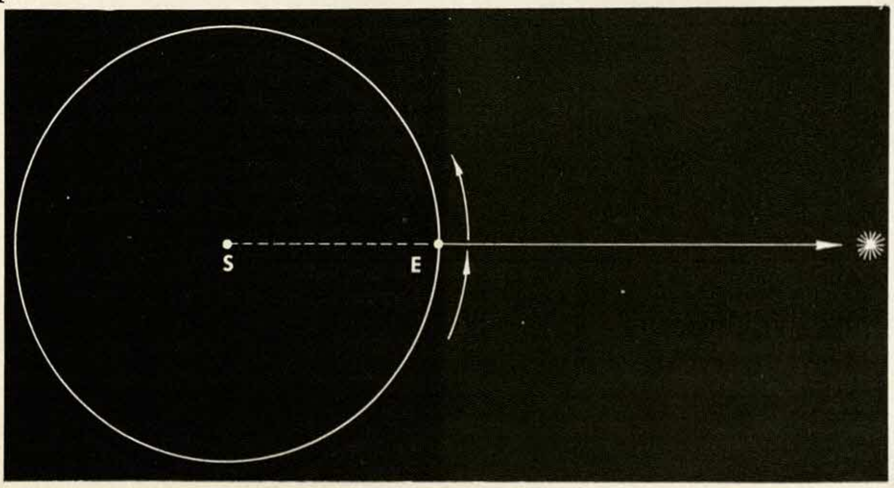
time is greater or lesser depending on whether the Earth is at perihelion or aphelion.

Moreover, even if the Earth revolved around the sun in a circular orbit at uniform speed, the sun would not reach its meridian at the same hour every day, because it is viewed from different—sometimes opposite—points of the Earth's orbit. Therefore, the sun appears to move among the stars; the line of this apparent motion is called the ecliptic, and is inclined to the celestial equator as the Earth's axis is inclined to its orbit. As a result, even if the sun followed its course along the ecliptic with uniform speed in all seasons, its motion as projected on the celestial equator would be variable. From December to January, for example, the motion of the sun on the ecliptic is equal to its motion on the equator, whereas in March it follows a shorter arc on the ecliptic than on the equator (see Illustration 4).

The combined effect of the ellipticity of the Earth's orbit (curve **a** in Illustration 5) and of the inclination of the ecliptic to the celestial equator (curve **b**) is to advance or delay the instant at which the sun crosses the meridian. This advance or delay, called the equation of time (curve **c**), has different values at different times of the year. After compensations have been made for arbitrary changes in time (daylight saving or summer time) and for the observer's position within the arbitrarily designated time zones, the instant of the sun's passage over the meridian can be determined by adding to 12:00 o'clock the number of minutes indicated for the appropriate time of the year. Interestingly, the four days each year when the midday marked on the instrument will coincide with the midday given by the radio time signal are April 15, June 14, September 1, and December 24.

THE CALENDAR | the measurement of time in the evolution of civilization

1



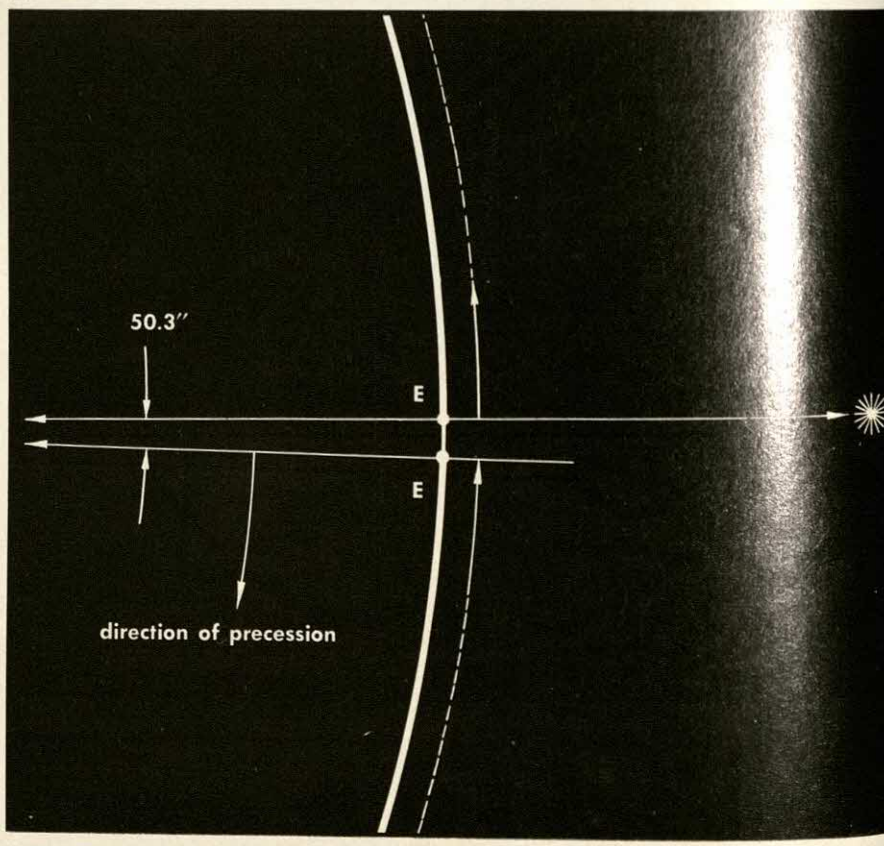
THE SIDEREAL YEAR—The [illegible] is the basic unit of time that must be sub[illegible]ded in order to construct a calendar. One [illegible]e commonly described types of year is th[illegible]dereal year, which is measured as follows[illegible]e Earth and the sun are aligned with a [illegible]d star. The sidereal year is the time requi[illegible] by the Earth to make one complete revolu[illegible] around the sun and return to exactly the [illegible]e alignment with the star. The length of t[illegible]idereal year is 365 days, 6 hours, 9 minute[illegible]9.5 seconds.

2

THE TROPICAL YEAR—The tropical year is the year of the seasons, the amount of time the Earth takes to circle from one vernal equinox to the next.

The seasons are caused by a tilt (of about 23½°) of the Earth's axis of rotation to the plane of the ecliptic. Because of precession the orientation of this tilt with respect to the fixed stars changes slowly with time. Therefore, the time required for the Earth to come back to the same season (a tropical year) is slightly different from the time taken for the Earth to come back to the same alignment of the Earth, sun and a star (a sidereal year). The length of the tropical year is 365 days, 5 hours, 48 minutes, 46 seconds—approximately 20 minutes shorter than the sidereal year. The ancient astronomers came very close to this figure when they arrived at a year of 365¼ days. In the tropical year, calendar dates always appear at the same season each year.

Another type of year is the anomalistic year. It is measured as the period of time necessary for the Earth to orbit the sun from one perihelion (the point in the orbit nearest the sun) to the next. This type of year is important only in the description of the movement of the Earth. It has no importance in the construction of the calendar.



The construction of a calendar is one of the first necessities of civilization, and one of the more intricate problems in astronomy.

All calendars divide time into days. The days are then grouped into fractions of a year—the weeks and months. Precise definitions of a day or a year vary, but certain criteria must be followed for practical reasons. One is that in a given region, the seasons always appear at the same time. If this were not so, the seasons would be displaced with respect to any given date, with spring arriving in the middle of August, for example.

The various types of calendars, their applications, and their histories make an interesting study.

3

LUNAR CALENDARS—The simplest and earliest of all types of calendars is the lunar calendar. Each month began with a "new moon," and important dates and events were linked to the movement and phases of the moon. A fixed lunar calendar has 12 months, alternating 29 and 30 days, and covers a year of 354 days. Illustration 3 shows the moon in one of its phases, roughly the third quarter, as the month wanes.

4

A LUNAR CALENDAR—The prime modern example of a lunar calendar is the Moslem calendar. Since its year is shorter than the tropical year, the beginning of the year can fall in any season. With this type of system, one year is gained for every 33 tropical years.

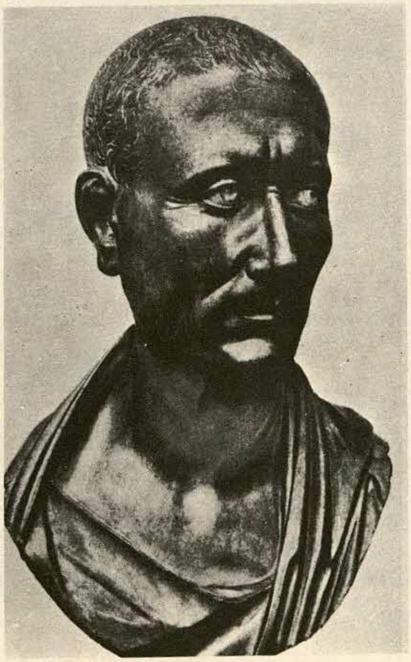
5

THE REFORM OF THE ROMAN CALENDAR—This ancient Roman calendar (Illustration 5b) dates from 753 B.C. Originally a lunar calendar, it began in the spring and had 10 months. Eventually, two more months were added, and the calendar became a luni-solar one, with an occasional thirteenth month added to keep in step with the seasons.

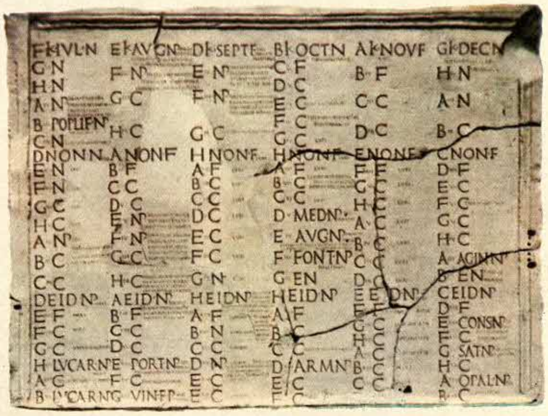
Julius Caesar (Illustration 5a) inaugurated a significant calendar reform, following the advice of the Alexandrian astronomer Sosigenes. The year 46 B.C. was made 445 days long—an addition of three months to correct the lag behind the sun created by the previous calendar.

Caesar adopted a solar calendar, with a year of 365¼ days—a figure determined by the ancient Egyptians. The year was divided into 12 months of unequal length, and an extra day was added to the month of February every fourth year (leap year). The vernal equinox was brought to March 25.

a



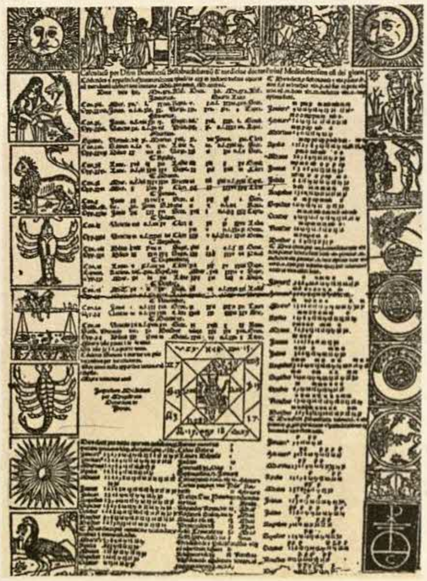
b



6

a

b



THE GREGORIAN REFORM — Because the length of the tropical year is approximately 11 minutes and 14 seconds less than the value used by Caesar, the accumulated error in the Julian Calendar amounts to one day every 128 years. By the year 325 A.D., at the time of the meeting of the Council of Nicea, the vernal equinox had fallen back to March 21.

By 1582, when Pope Gregory XIII (Illustration 6a) was in power, the vernal equinox had receded to March 11. With the help of the Jesuit astronomer Christopher Clavius, Pope Gregory worked out another calendar reform. In March, 1582, he abolished the Julian calendar, (Illustration 6b) and established January 1 as the beginning of the new year. He decreed that Friday, October 15, 1582, should follow Thursday, October 4, 1582. This action dropped 10 days from the year, and brought the vernal equinox back to March 21 for the following years. He also established a system of leap years designed to keep the calendar more in step with the tropical year. Leap years occur in every year divisible by four, except for the century years, which must be divisible by 400. The years 1700, 1800, and 1900, for example were not leap years, but the year 2000 will be.

The Gregorian calendar accumulates an error of only one day in more than 3,000 years. It is used in almost all of the Christian countries of the world.

7

A CALENDAR FOR SCIENTIFIC USE—A great many stars are visible in this region of the sky. A large percentage of them are stars whose brightness varies over long periods that have remained constant since they were first observed.

In determining the exact period of a variable star, the Gregorian calendar is an awkward yardstick; for example, leap years must be taken into account. To avoid much inconvenience, scientists use a system of calculation beginning with a hypothetical year zero of a fictitious era, called the Julian era, which starts on January 1, 4713 B.C. From this point on, dates are counted in days, beginning at midday. This system is used so that all of the events an astronomer observes in one night are listed under the same date. Using this type of calculation, January 9, 1925, corresponds to the Julian day 2,424,170. All astronomical events are dated within this system.

8

A PRIMITIVE CALENDAR—This old Sioux calendar uses a different symbol for each day. The calendars of primitive peoples did not often take the year into account; instead, these calendars were often based on phases of the moon.

9

SECTION I
Century letters

centuries	Julian Calendar B.C.	Julian Calendar A.D.	Gregorian Calendar
1	E	U	for use from Friday, October 15, 1582
2	R	N	
3	S	I	
4	U	V	
5	N	E	
6	I	R	
7	V	S	
8	E	U	
9	R	N	
10	S	I	
11	U	V	
12	N	E	
13	I	R	
14	V	S	
15	E	U	1582
16	R	N	E
17	S	I	R
18	U	V	U
19	N	E	I
20	I	R	E
21	V	S	R
22	E	U	U
23	R	N	I
24	S	I	E
25	U	V	R
26	N	E	U
27	I	R	I
28	V	S	E
29	E	U	R
30	R	N	U
31	S	I	I
32	U	V	E
33	N	E	R
34	I	R	U
35	V	S	I
36	E	U	E
37	R	N	R
38	S	I	U
39	U	V	I
40	N	E	E
41	I	R	R
42	V	S	U
43	E	U	I
44	R	N	E
45	S	I	R
46	U	V	U
47	N	E	I
48	I	R	E
49	V	S	R
50	etc.	etc.	etc.

SECTION II
Year within the century (leap years are indicated in bold type)

				U	N	I	V	E	R	S
1	29	57	85	3	2	1	0	6	5	4
2	30	58	86	4	3	2	1	0	6	5
3	31	59	87	5	4	3	2	1	0	6
4	**32**	**60**	**88**	**0**	**6**	**5**	**4**	**3**	**2**	**1**
5	33	61	89	1	0	6	5	4	3	2
6	34	62	90	2	1	0	6	5	4	3
7	35	63	91	3	2	1	0	6	5	4
8	**36**	**64**	**92**	**5**	**4**	**3**	**2**	**1**	**0**	**6**
9	37	65	93	6	5	4	3	2	1	0
10	38	66	94	0	6	5	4	3	2	1
11	39	67	95	1	0	6	5	4	3	2
12	**40**	**68**	**96**	**3**	**2**	**1**	**0**	**6**	**5**	**4**
13	41	69	97	4	3	2	1	0	6	5
14	42	70	98	5	4	3	2	1	0	6
15	43	71	99	6	5	4	3	2	1	0
16	**44**	**72**	**100**	**1**	**0**	**6**	**5**	**4**	**3**	**2**
17	45	73		2	1	0	6	5	4	3
18	46	74		3	2	1	0	6	5	4
19	47	75		4	3	2	1	0	6	5
20	**48**	**76**	for centennial years which are not leap years	**6**	**5**	**4**	**3**	**2**	**1**	**0**
21	49	77		0	6	5	4	3	2	1
22	50	78		1	0	6	5	4	3	2
23	51	79		2	1	0	6	5	4	3
24	**52**	**80**		**4**	**3**	**2**	**1**	**0**	**6**	**5**
25	53	81		5	4	3	2	1	0	6
26	54	82		6	5	4	3	2	1	0
27	55	83		0	6	5	4	3	2	1
28	**56**	**84**		**2**	**1**	**0**	**6**	**5**	**4**	**3**

SECTION III

January	February	March	April	May	June	July	August	September	October	November	December
2	5	5	1	3	6	1	4	0	2	5	0

SECTION IV

0	SUNDAY
1	Monday
2	Tuesday
3	Wednesday
4	Thursday
5	Friday
6	Saturday
7	SUNDAY
8	Monday
9	Tuesday
10	Wednesday
11	Thursday
12	Friday
13	Saturday
14	SUNDAY
15	Monday
16	Tuesday
17	Wednesday
18	Thursday
19	Friday
20	Saturday
21	SUNDAY
22	Monday
23	Tuesday
24	Wednesday
25	Thursday
26	Friday
27	Saturday
28	SUNDAY
29	Monday
30	Tuesday
31	Wednesday
32	Thursday
33	Friday
34	Saturday
35	SUNDAY
36	Monday
37	Tuesday
38	Wednesday
39	Thursday
40	Friday
41	Saturday
42	SUNDAY

A PERPETUAL CALENDAR—Perpetual calendars run into difficulty because the year cannot be divided into 52 complete weeks, and because of the arrangement of leap years.

This perpetual calendar (Illustration 9) is valid for the Julian as well as Gregorian calendar. Although it is limited here to the years 5000 B.C. to A.D. 5000, it can be extended into infinity by continuing the progression of the letters UNIVERS—one for each century after A.D. 5000 or before 5000 B.C.

With this calendar, it is possible to determine the day of the week corresponding to a certain date. To find on what day January 22, 1286, A.D. occurred: (1) Look in Section I and find the letter corresponding to the century—in this case the thirteenth century A.D. The letter is found in the second column, and is an *R*. The Julian calendar was in use at the time. (2) In Section II, find the year within the century—in this case 86. (Bold type indicates leap years.) Follow across the columns until the number under *R* is reached. The number is 6. (3) In Section III, take the number corresponding to the month—in this case 2 for January, and add it to the number from Section II: 2 + 6 = 8. (If the date occurs during January or February of a leap year, decrease this number by one.) (4) To this number, add the date being used—in this case January 22: 8 + 22 = 30. The day of the week corresponding to this number is found in Section IV. January 22, 1286, occurred on a Tuesday.

Dates after 1582, when the Gregorian calendar was put in effect, are figured in the same way, but using the third column of letters in Section I.

MERCURY | the sun's "moon"

It is said that the sixteenth-century Polish astronomer Nicholas Copernicus, as he lay on his deathbed, lamented the fact that he never had seen the planet Mercury. It is possible that Copernicus, despite his long study of the sun and its retinue of planets, may not have been fortunate enough to sight Mercury. Blotted from sight most of the time by the sun's glare, Mercury is the most elusive of all the planets.

The most ancient recorded observations of Mercury date back to 246 B.C. It was, in fact, observed and studied by the Egyptians, Romans, and Greeks centuries before development of the telescope. Because its orbit is much closer to the sun than that of the Earth, Mercury is visible only for a short time, at dusk or dawn. These dusk and dawn sighting periods led ancient stargazers to believe that two separate planets rode the heavens close to the sun.

OBSERVING MERCURY

Mercury can be seen with the naked eye only when the sun is just below the horizon. If the sun is already low beneath the horizon, Mercury likewise is very low and is often obscured by mist and haze. On the other hand, when the setting sun is not far enough below the horizon—or, if in the early morning, the sun has already risen too high—its overpowering light masks the comparatively weak reflection from Mercury. Thus, sighting Mercury depends on being in the right place at the right time, and on favorable atmospheric conditions.

When it is not hidden by the sun's brilliance—and when its orbit takes it farthest from the sun—Mercury shines like a star with a magnitude of −1.2, a luminosity equal to that of Sirius. During these brief periods of ideal dusk and dawn observation, Mercury appears as the evening or morning star, frequently radiating a starlike twinkling because of its small size and its low altitude on the horizon.

AN EXCEPTIONAL PLANET

In many ways Mercury is an exceptional planet. It is the smallest of the smaller planets; its 3,000-mile diameter is not much larger than that of the Earth's moon. Indeed, its small size and faint markings, as described by the American astronomer Edward Emerson Barnard, who was astronomer of Yerkes Observatory at the University of Chicago (1895–1923), give Mercury a resemblance to the moon. It is the closest planet to the sun; it has the smallest mass and the highest density of all the planets. With the exception of Pluto, its orbit is the most elliptical (eccentricity = 0.2) of all the planets, and the most highly inclined (7°) to the median plane of the orbits of the other planets.

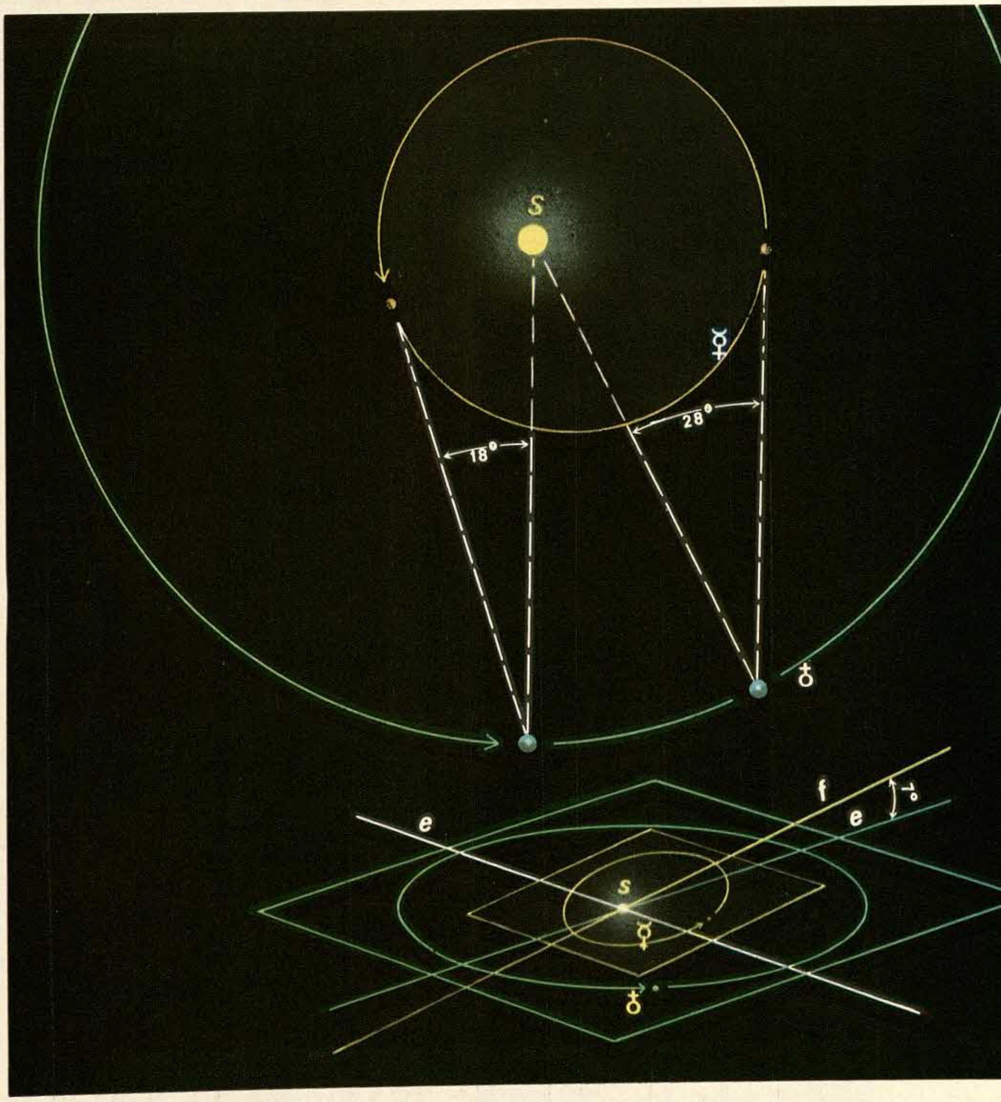
MERCURY'S ELLIPTICAL ORBIT

Mercury's orbit has an elliptical shape that brings it as close as 28 million miles to the sun, and swings it as far away as 43 million miles. However, because the Earth and Mercury orbit the sun in the same direction, Mercury appears to move closer to the sun every 116 days.

To observe Mercury intelligently, it is essential to know the peculiarities of its orbit. Twice during the Earth year—in the spring as an "evening star" and in the autumn as a "morning star"—Mer-

AN EXCEPTIONAL ORBIT—Of all planetary orbits, Mercury's is one of the most unusual because of its eccentricity and inclination with respect to the median plane of other planetary orbits. In terms of visibility, Mercury's orbit, at the time of maximum elongation, causes the planet to be visible either farthest from or nearest to the sun, according to the relative positions of the sun, Mercury, and the Earth. The angle of maximum elongation varies from 18° to 28°.

1



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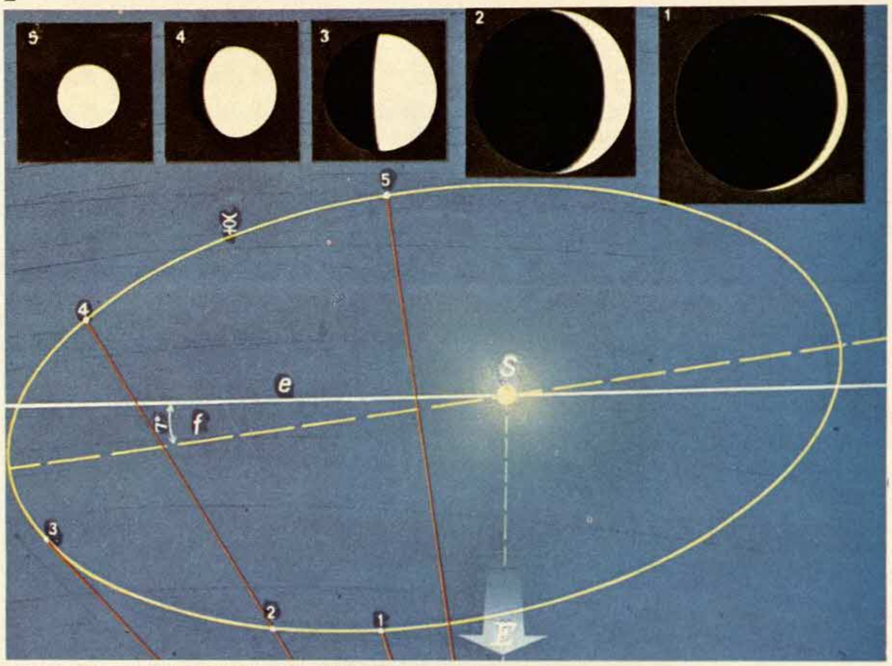


APPARENT DIMENSIONS OF MERCURY— Depending on its orbital position, Mercury appears smaller or larger to the observer on the Earth. In the illustration, the relative dimensions of the planet are reproduced at different points in its orbit, represented on a scale of 2 mm (one second of arc). At its minimum distance from the Earth (position 1), Mercury has an apparent diameter of 13 seconds; its disk appears almost totally dark. At the maximum distance (position 5), its diameter is 5 seconds; at the maximum elongation (position 3), its diameter is 8 seconds. This is the best orbital position for observation.

cury's position is most favorable for observation. Actually, however, there are six periods in the Earth year when Mercury is aligned properly for viewing at the inner precincts of the solar system. These periods occur when Mercury seems, from observation points on Earth, to be at the easternmost or westernmost orbits away from the sun. These periods are known as greatest eastern elongation, when Mercury appears as an "evening star," and greatest western elongation, when it is a "morning star." The time taken for Mercury to return to the same elongation is its synodic month (about 116 days). The elongations are thus spaced about two months apart, and each lasts for about two weeks. During these periods, Mercury is visible for about an hour at a time.

The best time for observing Mercury's surface with a telescope occurs when the planet is on the far side of the sun, at which time it presents a brightly illuminated hemisphere to Earth viewers. Unfortunately, however, at this time Mercury is on the side of the sun farthest from the Earth, and thus appears very small because of its distance. At this position, it appears as a small disk with a diameter only 1/360 that of the moon.

Mercury is best observed during periods of maximum elongation. However, maximum elongation is not necessarily always enough to ensure good viewing. Imagine, for example, that Mercury's maximum elongation occurs during the autumnal equinox and that, at this time, the planet is in its "eastern" phase, or visible in the evening sky to the left of the sun. At such a time, the planet is low on the horizon, even though it is distant from the sun. Under such conditions, the viewing of Mercury is difficult because it must be sighted along the line of the ecliptic, which, at sunset during autumn, is below the celestial equator.

On the other hand, if the autumnal elongation is in the "western" phase, with the planet visible in the dawn's light, an observer finds Mercury high on the ecliptic, even if its distance from the sun is less, as the ecliptic is strongly inclined in relation to the horizon.

These situations can be accentuated by the fact that Mercury's orbit is inclined approximately 7° with respect to the ecliptic. Thus, whenever observational conditions are particularly favorable, Mercury appears clearly visible high on the horizon. These periods occur about every third synodic period for a given eastern or western elongation, or every 348 days.

PHYSICAL CHARACTERISTICS OF MERCURY

The mass of a small planet is not easy to determine. Generally, a reliable method is to observe the perturbations the planet causes in the motion of other celestial bodies that pass near it. Mercury has no satellites, however, so when comets or asteroids pass close, astronomers follow their movements closely to determine an accurate value for Mercury's mass. Current astronomical calculations, based on a close pass of the minor planet Eros, place Mercury's mass at 0.054, and its density at 5.61 times that of water—slightly higher than the density of the Earth.

Because Mercury's mass is small, astronomically speaking, the acceleration of gravity on its surface is weak, 382 cm/sec² (about 13 ft/sec²) as against 980 cm/sec² (about 32 ft/sec²) on the Earth.

If molecules of any gas were present on Mercury's surface, they would escape easily because of the low velocity (about 4.3 km/sec or 2.67 mi/sec) necessary to overcome the force of gravity. Furthermore, because Mercury is so close to the sun, the great heat generated by solar radiation would exert intense temperatures on the gas and result in an increase in velocity strong enough to force the molecules off the planet. As a result, Mercury probably has little or no atmosphere. Hydrogen atoms have been detected spectroscopically on Mercury, implying a very thin atmosphere, but the quantity of gas must be so small as not to constitute an atmosphere in the ordinary sense.

THE SURFACE OF MERCURY

Because of Mercury's extremely small size and its distance from the Earth, it is extremely difficult to observe details of the planet's surface. Observed in twilight, Mercury's surface details are invisible because of the great thickness of the Earth's atmosphere through which the planet's reflected light must travel. Because of this, astronomers prefer to observe Mercury by day, when, in spite of the light of the sun, the planet's telescopic image appears more clearly than by evening light.

Details of Mercury's surface were first observed in the early nineteenth century. The first precise observations from which a map of the planet was drawn were made by the Italian astronomer, Giovanni Schiaparelli, near the end of the last century. Schiaparelli's map, pinpointing faint permanent markings on the planet, has not been substantially modified by subsequent observations. The hazy, indistinct patches that can be seen only with difficulty on Mercury's surface cannot be interpreted with certainty. It

is not known whether they are mountains, depressions, or simply zones where the reflecting power of the planet's surface differs from that of surrounding areas.

THE ROTATION OF MERCURY

Drawings of the faint surface markings on Mercury led early twentieth-century astronomers to conclude that Mercury rotates with the same period as its revolution about the sun (synchronous rotation), thus keeping one face perpetually toward the sun. The result, of course, would be a very hot surface on the sunlit side. Calculations showed that the sunlit face would reach temperatures hot enough to melt lead while the dark side would have temperatures far below zero.

This view persisted until 1965, when radar observations of Mercury made with the 1,000-foot radio telescope at Arecibo Ionospheric Observatory in Puerto Rico showed a rotation period of about 59 days rather than the expected 88 days. (The technique of determining the rotation of a planet by radar is accurate but somewhat time-consuming.) It was quickly pointed out by theoretical astronomers that a rotation period of exactly two thirds of the orbital period would be expected for Mercury. The explanation lies in the fact that Mercury's orbit is rather eccentric, and a rotation period that allows the same face of Mercury to face the sun at each alternate perihelion passage would be more stable than other possible periods; that is, the rotation and orbital periods would be "locked-in" to one another and would maintain the 2/3 ratio.

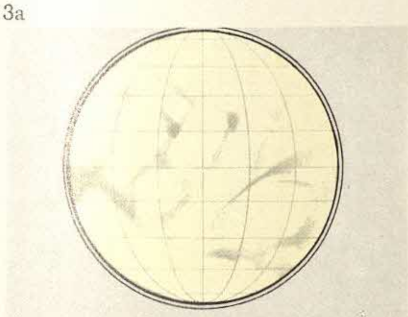
The 59-day period is the sidereal rotation period or the period as seen by an observer fixed in space. An observer on Mercury, however, would see the sun rise each 180 Earth days (since $1/59 - 1/88 = 1/180$). This 180-day period is called the Mercurian solar day.

The radar rotation period contradicted the visual observations of Mercury, which had shown a synchronous rotation period. The explanation of this discrepancy illustrates the need for occasional enlightened skepticism in science. The surface markings on Mercury are indeed faint and require a trained observer for effective study. Their existence is indisputable, however, since drawings made independently by different observers agree reasonably well. Still, it is easy to see in retrospect how even correct drawings gave the wrong rotation period.

As previously mentioned, favorable conditions for observing Mercury occur at intervals of three synodic periods for a given eastern or western elongation. It so happens that three synodic periods (about 348 days) is very nearly two Mercurian solar days, so that at each favorable eastern elongation the same face of Mercury is illuminated. The same is true of western elongation, except that the opposite face is illuminated. If the viewer always observes the same face of Mercury at eastern elongation and the opposite face at western elongation, the natural conclusion is that Mercury rotates with the same period as its orbital motion. It is sheer coincidence that favorable elongations are spaced so that observers miss those occasions when different faces are presented. Since the periodicity persists for a half dozen years, it is not surprising that maps based on only a few years' observations were interpreted as proof of synchronous rotation. The 59-day period was verified by calculating the interaction of gravity forces and tidal effects on the planet.

SIXTY YEARS OF OBSERVATION — These maps of Mercury show the progress of sixty years of telescopic observation. The maps represent a synthesis of the years of observation, and are respectively by Schiaparelli, 1899 (3a); Antoniadi, 1934 (3b); Rudeaux, 1928 (3c); Jarry Desloges, 1920 (3d); McEwen, 1936 (3e); and Dollfus, 1953 (3f). The first four drawings are similar; the last two different. This discrepancy may be attributed to the observation of different faces of Mercury. In these drawings, contrast has been greatly exaggerated. The three drawings in the right-hand column, made by Dollfus, are a synthesis of observations made with photographs.

3a



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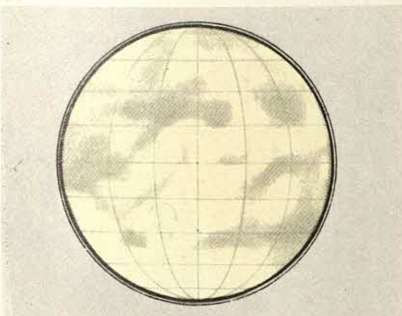

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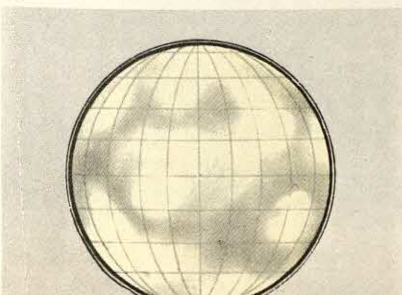

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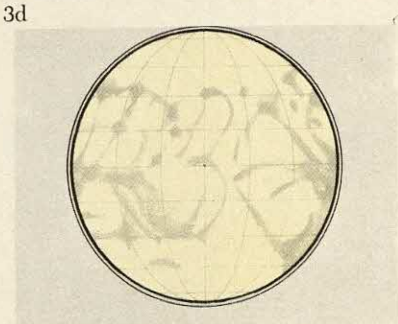

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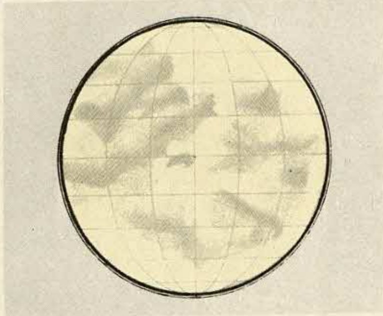

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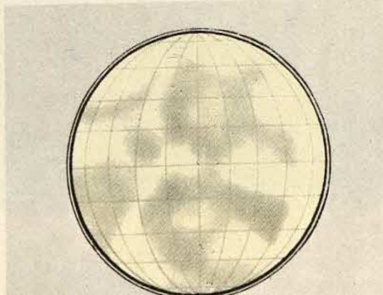

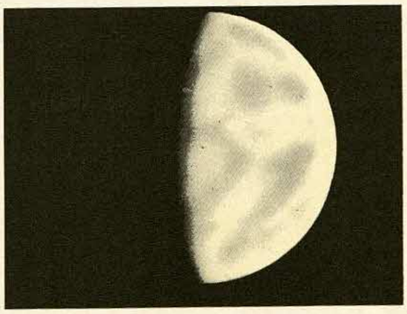

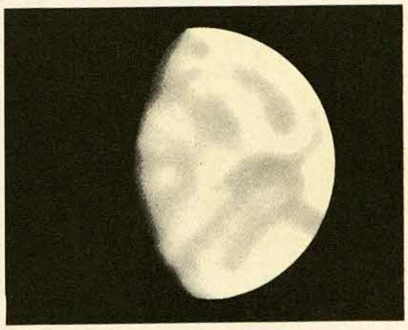

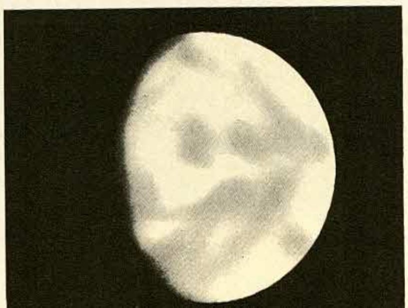

VENUS | the Earth's twin

The brightest "star" in the night sky is not a star at all; it is the planet Venus, often called the Earth's twin. Venus sometimes shines with a magnitude of −4.3, fifteen times the brightness of the brightest star, Sirius. The light from Venus is so bright that human eyes well accustomed to darkness away from the lights of a town can see the shadows it casts. With proper exposure it is possible to take photographs with the light from Venus. The bright planet is visible in the night sky for only a short time after sunset and for only a brief period before sunrise, a characteristic which led the ancient Greeks to conclude that Venus was two different heavenly bodies. They called it the planet Phosphorus in the morning and Hesperus in the evening. The ancient Romans named this very bright object Venus, after the goddess of beauty.

THE ORBIT OF VENUS

Venus is one of two planets whose orbit is nearer the sun than the orbit of the Earth. The orbit of Mercury is nearest the sun, and there are many points of similarity between Mercury and Venus as they appear in the sky. Both appear near the sun, either to the west or to the east, although Venus is more distant from the sun than is Mercury. Throughout its orbit Venus maintains almost the same distance from the sun, with an average orbital radius of 108 million km (about 67 million mi). No other planet has such an unelliptical orbit. The average radius of the Earth's orbit is 149 million km (about 93 million mi), and the two planets move closer together or farther apart according to whether Venus is on

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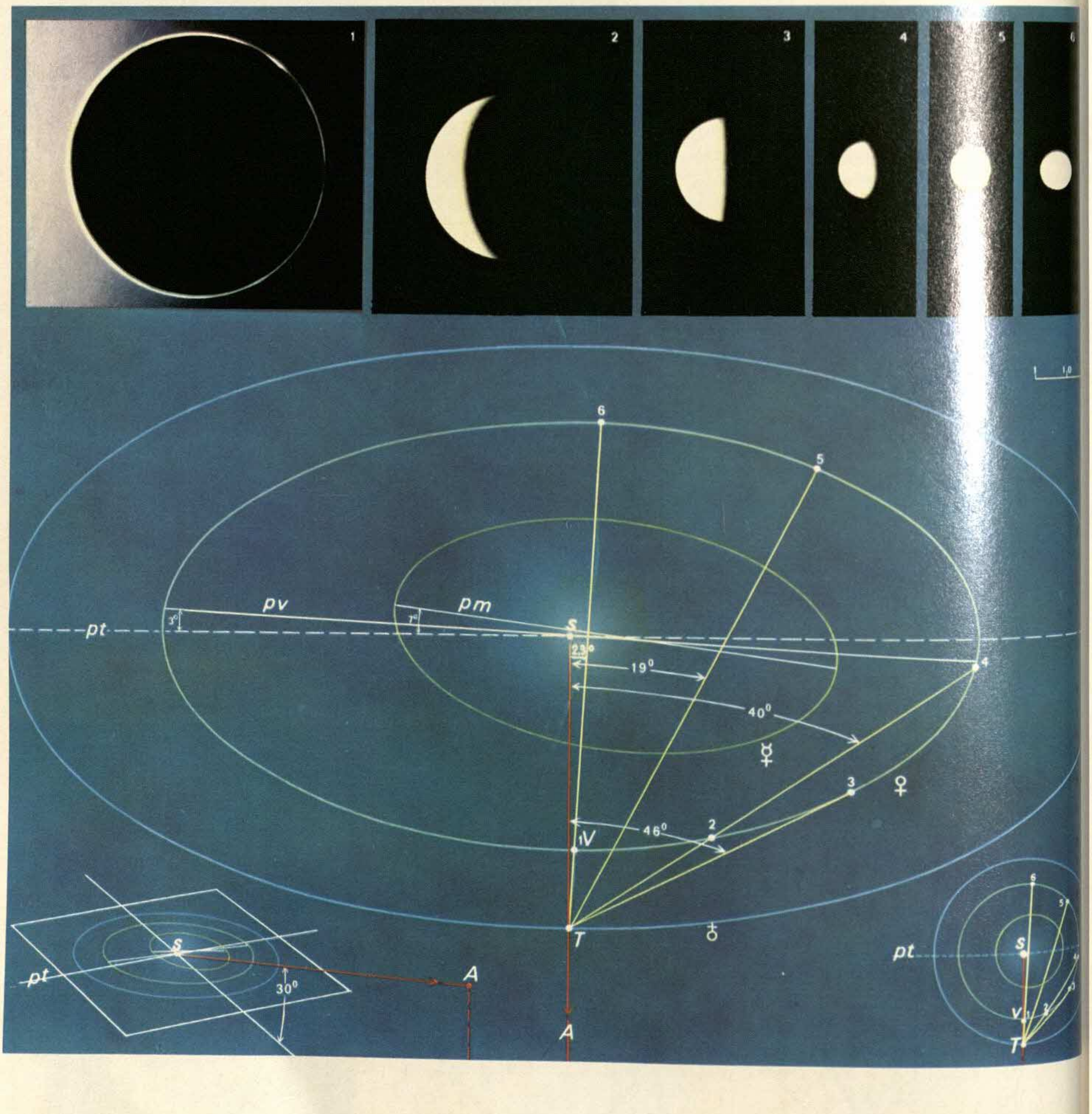


the same or opposite side of the sun as the Earth. When Venus is between the Earth and the sun, its distance from the Earth averages, at minimum, 41 million km (about 25.5 million mi). No other celestial body except an occasional comet or asteroid (and the moon) comes nearer the Earth. In its nearest position, the disk of Venus seen from the Earth appears very large, subtending about 65″ (seconds of arc), or about one-thirtieth the diameter of the moon.

When Venus and the Earth are on opposite sides of the sun, the distance between the two planets is almost twice the distance between the Earth and the sun. The apparent diameter of Venus as seen from the Earth is 10″, much more than that of Mercury in the same position, but 6½ times less than when it is at minimum distance from the Earth. Venus completes its orbit in 225 days, slightly less than two-thirds the time taken by the Earth to circle the sun. However, Venus and the Earth are in the same relative positions with respect to the sun only when Venus has caught up with the Earth, which occurs about every 584 days. So, when Venus appears brilliant in the evening, high above the horizon, it will appear again in the same way a year and seven months later. The inclination of the orbit of Venus with respect to the ecliptic is only 3°25′. Because of this small inclination the planet is never seen rising or setting much below the ecliptic.

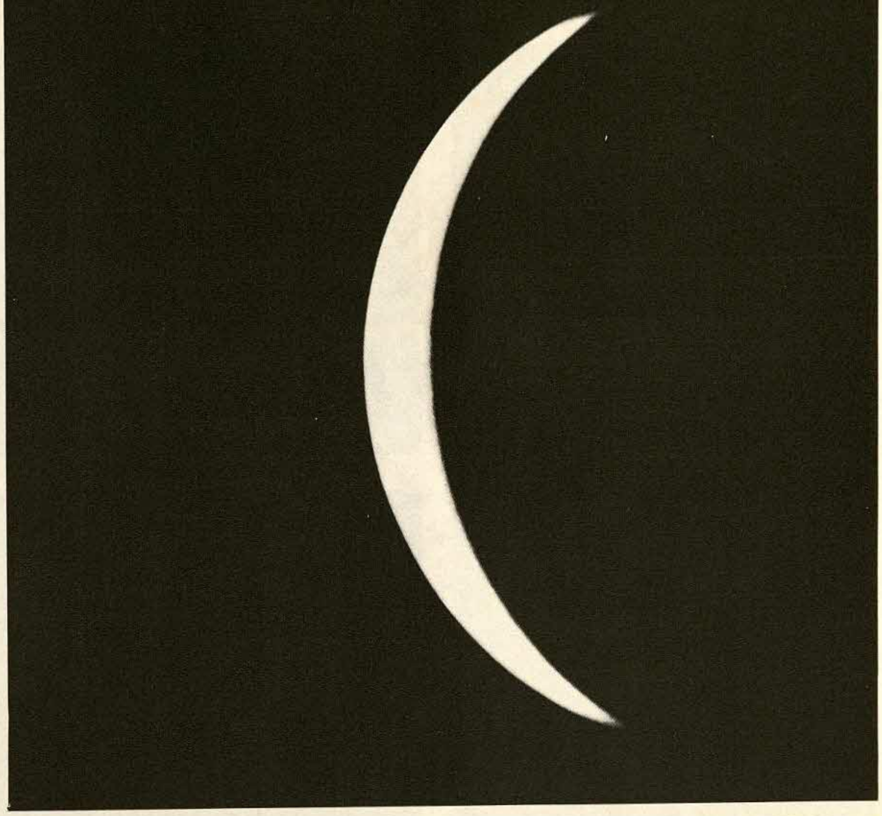
PHYSICAL PROPERTIES

The diameter of Venus is 12,200 km (about 7,580 mi), only slightly less than that of the Earth. This similarity in size is one reason why Venus and Earth are called twin planets. Taking the mass of the Earth as 1, that of Venus is .8073.

OBSERVATION BY TELESCOPE

Because of the large apparent diameter of Venus, relatively small telescopes will reveal that it shows phases similar to those of the moon and of Mercury. Galileo was first to note the phases of Venus.

THE PHASES AND ORBIT OF VENUS—The six illustrations at the top show the different phases of Venus through a telescope employing the same magnification for each observation. When Venus is at minimum distance from Earth, the dark hemisphere is turned toward Earth. The orbit of Venus, marked with the symbol ♀, is almost perfectly circular and smaller than that of the Earth (designated ♁), but larger than that of Mercury (designated ☿). The distance between Earth and Venus varies according to the positions of Venus (designated from 1 to 6 on the orbital path).



A MISLEADING APPEARANCE—The first time Galileo saw Venus through a telescope, he was impressed by its strong resemblance to the moon, as seen in this photograph showing Venus close to its minimum distance from Earth. The surface of Venus appears almost completely uniform, although the points of the crescent are not quite alike.

Through his telescope, the planet did not appear perfectly round, but crescent-shaped. The Ptolemaic theory of the disposition of celestial bodies conceded that Venus had phases, but only those in the shape of a narrow crescent. However, Galileo early in the seventeenth century observed an intermediate phase of Venus between half and full disk, an observation that provided the basis of argument for the Copernican theory.

An observer seeing Venus through a telescope is struck first by the dazzling light of the planet. Because Venus is nearer the sun than the Earth, it receives double the amount of light received by the Earth. The surface of Venus is so reflective that 59 percent of the light that reaches the planet is reflected back into space. Mercury and the moon have much less ability to reflect. Only 7 percent of the light reaching Mercury is reflected. Such a large difference between the reflecting powers of Venus and Mercury is attributed to the presence on Venus of an atmosphere always covered by clouds, which reflect light much more effectively than does any rock surface.

Details of Venus are difficult to observe. A small telescope reveals that the two horns of the crescent are not shaped equally. A more powerful instrument will show faint dark areas that appear from time to time on the surface of the cloud mantle which covers Venus. These areas change rapidly in appearance and generally are visible for only a short time.

It is possible to make quite good photographs of Venus. Photographs taken with ultraviolet light best show the dark areas of the planet. Such photographs are taken through a telescope on black-and-white film sensitive to ultraviolet light, using a filter that excludes all visible wavelengths and allows only ultraviolet light to pass through. When Venus is photographed with white light or infrared light, the dark areas are barely visible, pointing to the conclusion that the darker areas represent atmospheric phenomena and not surface markings.

ATMOSPHERE

Venus is covered by a thick atmosphere whose nature was largely unknown before the flights of the Russian spacecraft Venera 4 and the American spacecraft Mariner 5. The two spacecraft were launched within two days of one another in June 1967. Mariner 5 passed within 4,000 km (about 2,500 mi) of the surface of Venus and made indirect measurements of atmospheric conditions. Venera 4 ejected a parachute-equipped capsule that telemetered data on the atmosphere as it floated to a soft landing on the night side of the planet.

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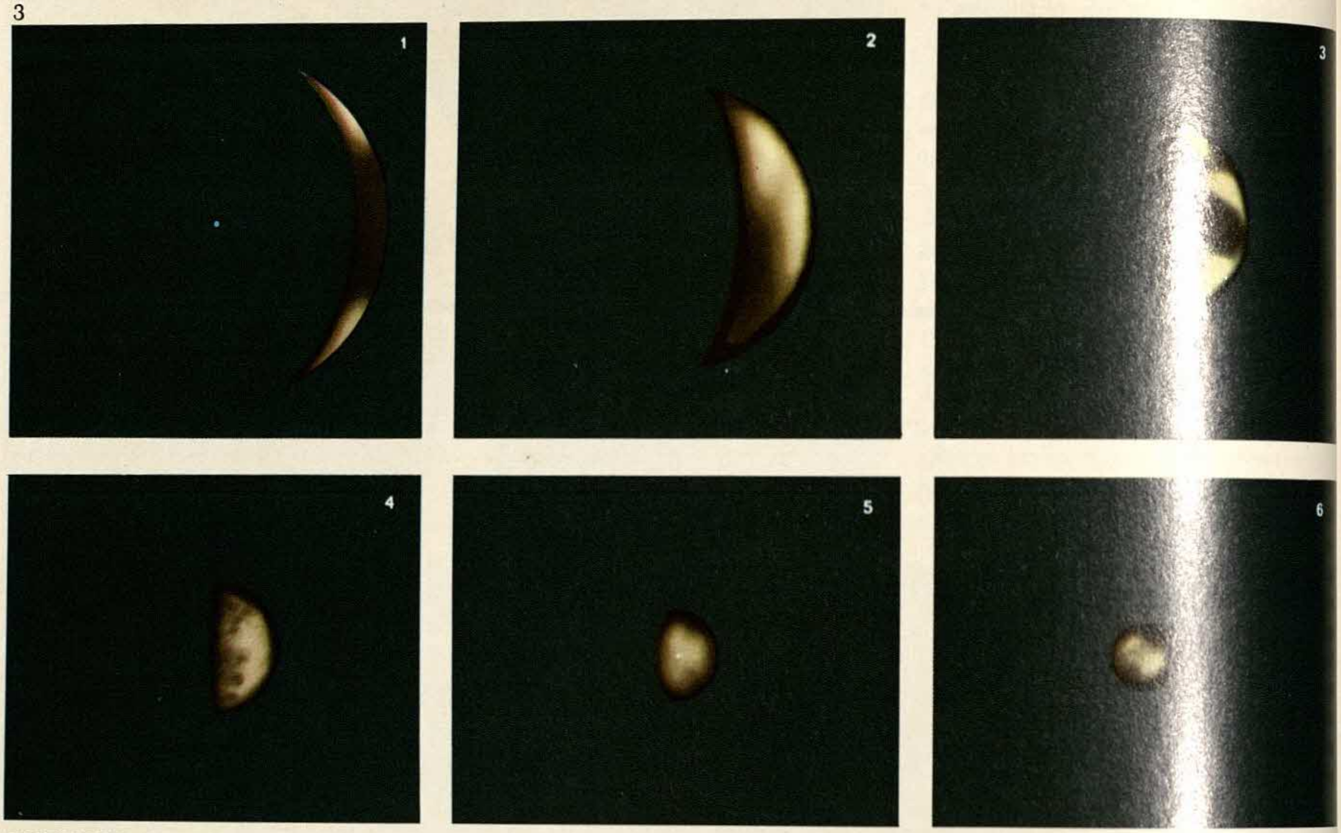

OBSERVATIONS—These recent photographs show the contrast of the patches visible on Venus as much exaggerated. The positions in which Venus was observed correspond to those of the six illustrations at the top of Illustration 1.

From microwave observations of Venus, the temperature of the planet had been thought to be very high—about 700° K (about 801° F). However, scientists were not sure whether the microwaves were originating from the surface or from high in the atmosphere. The Venera 4 data showed that the surface temperature on the night side of the planet was indeed very high—about 550° K (about 351° F). The temperature is expected to be about 100° K hotter on the day side. The Mariner 5 measurements gave a surface temperature of 700° K (about 801° F). The discrepancy could be explained if Venera 4 landed in a region where the elevation is 20 km (about 12.4 mi) higher than average.

The atmospheric pressure at the surface of Venus is very high compared to that of the Earth's atmosphere, but the exact value is in doubt because Venera 4 and Mariner 5 gave very different results. The Venera 4 data indicate a surface pressure about 18 times the Earth's atmospheric pressure at sea level, while the Mariner 5 data indicate 65 atmospheres. Again, the discrepancy might be explained if Venera 4 landed on a very high mountain or plateau, or if radio transmission from Venera 4 ceased before the capsule actually reached the surface.

The Venusian atmosphere was found to consist of 90 percent carbon dioxide. The remainder is probably mostly nitrogen along with about 1 percent oxygen. An attempt was made to detect the presence of water vapor, because water has an important bearing on the nature of the Venusian clouds and on the possible existence of life on Venus. Water was detected by Venera 4, and a combination of the data from Venera 4 and Mariner 5 indicate that about 0.1 percent of the atmosphere is water vapor.

Because of the very high temperature at the surface, all the water present on Venus must be vaporized. Even when the fact that Venus's atmosphere is much more dense than the Earth's is taken into account, indications are that Venus is a very dry planet, having only about 1/10,000 the water present on the Earth's surface. This is probably not enough water to explain the clouds of Venus as water vapor clouds, and the exact nature of the clouds remains uncertain.

One of the most intriguing questions raised by these observations is why the Venusian atmosphere is so different from the Earth's. Both planets have practically the same mass and size and their distances from the sun are similar. Yet one planet evolved an atmosphere with an abundance of oxygen and water necessary to life, while the other has an atmosphere consisting largely of carbon dioxide with very little water. It seems probable that the original atmospheres of the two planets came from their interiors soon after their formation about 4 billion years ago, in much the same way that volcanic gases still occasionally issue from fissures on Earth. Assuming that Venus and the Earth were formed from the same kind of material early in the history of the solar system, it is logical to assume that they should have emitted similar gases to produce their respective atmospheres.

It is undoubtedly significant that the amount of carbon dioxide incorporated within carbonate rocks on Earth (such as the limestone beds laid down by oceans) is very close to the total amount of carbon dioxide found in the Venusian atmosphere. Since carbonate rocks need water to form (either by way of marine organisms or chemical reactions involving water), the low concentration of carbon dioxide in the Earth's atmosphere may be due to the presence of oceans, or to the rise of life itself in these oceans. Although this may explain the difference in carbon dioxide concentration on the two planets, the puzzle of the very different amounts of water still remains.

The rotational period of Venus is 243 days—the longest in the solar system. The direction of rotation is retrograde, opposite to the directions of rotation of all the other planets and also opposite to the direction of revolution of all planets, including Venus, about the sun.

THE MOTION OF THE EARTH | from Ptolemy to space probes

For thousands of years, men observed the sky as if the Earth were immobile in the midst of a firmament that rotated about them. They did not know the shape of the Earth itself: some thought it was a flat disk, others visualized it as spherical or cubic. They saw the sky as a sphere about them; the more acute observers saw it as many transparent spheres, each rotating independently, to explain the different motions of the bodies they saw floating in its depths. Thus one sphere could support the sun, another the moon, with other spheres for the planets and the stars.

Although the hypothesis that the Earth itself was a moving body in space had been introduced during the Greek-Alexandrian epoch, this heliocentric hypothesis fell into oblivion through the influence of Ptolemy's great book, the *Almagest*, wherein he illustrated the geocentric hypothesis of the disposition of celestial bodies. The heliocentric hypothesis was not revived until the Renaissance, by Copernicus, and even then met lively opposition.

The root of all argument on the rotation or immobility of the Earth in space is the fundamental fact that different observers can judge a motion in different ways. The movement of a body can be easily perceived by an observer external to the body itself, while an observer participating in the motion of that body will think of it as still. For men, who are part of the Earth's motion, experiments far more refined than those available to the ancients are required to prove that their platform is itself moving in space.

The changing positions of celestial bodies observed in the sky—whether observed in the course of one night, or through different nights of the year—can be equally well explained by a heliocentric

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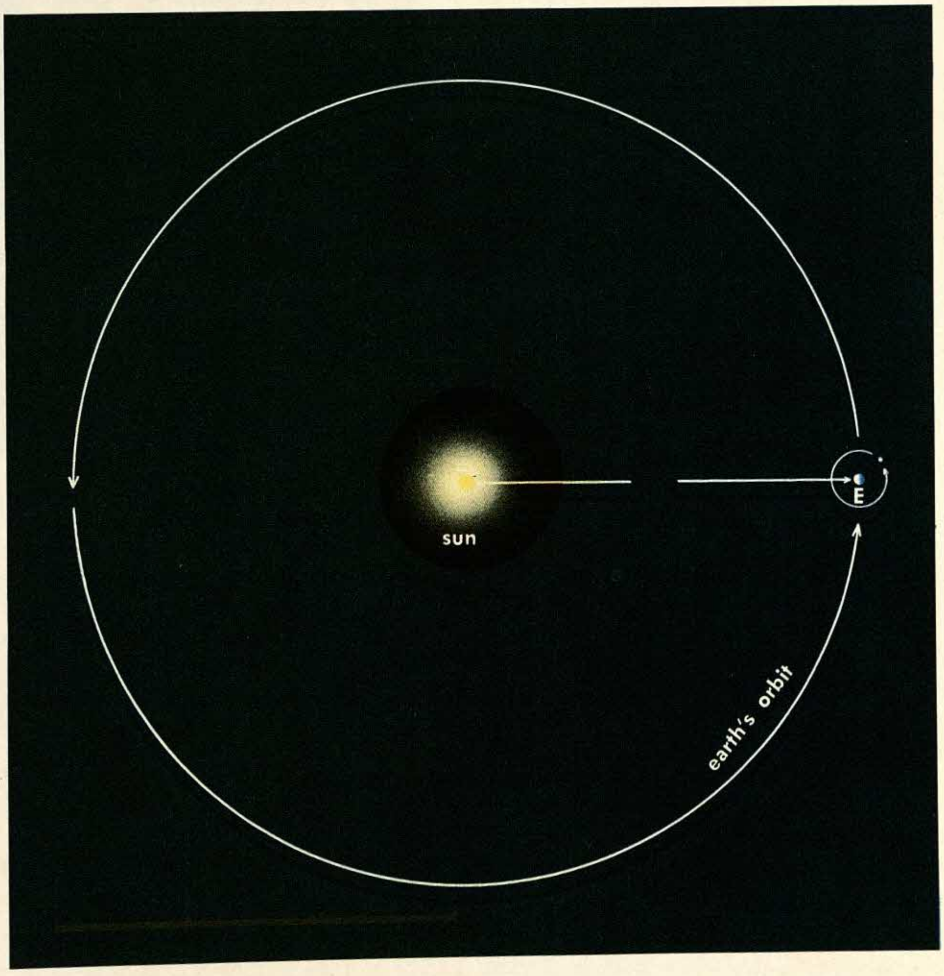


THE EARTH'S REVOLUTION AROUND THE SUN—The motion of the Earth most evident to a terrestrial observer is its rotation. The alternation of day and night is the obvious result of this rotation. From an astronomical point of view, however, the most important movement of the Earth is its revolution around the sun. Observation of this movement requires attention to the changing pattern of the night sky on different nights of the year. From this, it can be seen that the stars are continuously changing their positions because the visible zone from any general point on the Earth's surface depends on the hour and date of the year and, therefore, on the Earth's position in its orbit around the sun.

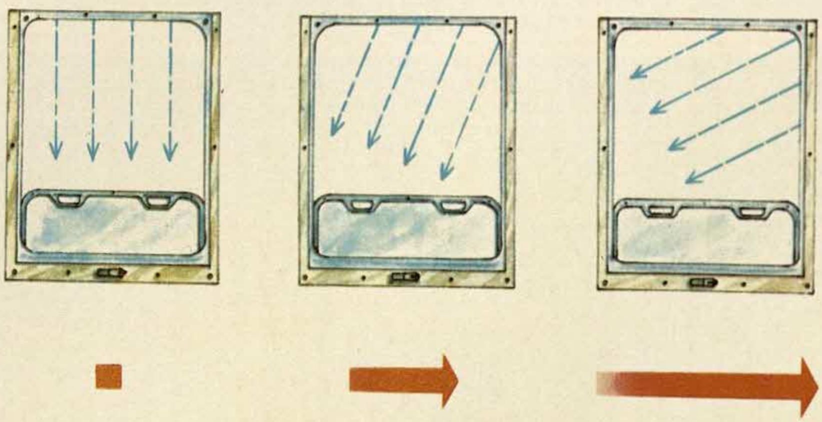
The orbit of the Earth is not perfectly circular, but elliptical. The ellipse is quite close to a circle, with a small eccentricity equal to 0.0167. The major semiaxis of this orbit is taken as a unit measure of astronomical distance: the astronomical unit, or AU

The mean distance of the Earth from the sun is about 149.4 million km (about 92.9 million miles). The Earth covers its orbit at a speed of about 29.79 km/sec (about 18.52 mi/sec) in a counterclockwise direction as observed from the north pole of the orbital plane. This direction of rotation is referred to in astronomy as direct; the opposite direction is retrograde. The time required for the Earth to make one complete revolution around the sun, so that the Earth, sun, and one star return to the same alignment (a sidereal year) is measured in mean solar days and results in 365.2564 of these units.

(Copernican) hypothesis or a geocentric (Ptolemaic) hypothesis. To select the Copernican hypothesis it is necessary to make some refined observations. Some of the complications of the Earth's motions that are reflected in the apparent motions of other celestial bodies cannot be explained by the Ptolemaic hypothesis, while the Copernican hypothesis allows a simple explanation.

Such improvements in observation contributed to the evolution of the Ptolemaic idea toward that of the Copernican. Initially, Copernicus' reintroduction of the heliocentric hypothesis—in opposition to the hypothesis of Ptolemy—had been suggested by the fact that the heliocentric positions of planets allowed a geometric description of their motion—a description much simpler than that possible under the Ptolemaic system. Following this line of thought, it was possible to refine knowledge of the motions of the planets—particularly that of the Earth's motion—so that it became increasingly difficult to support objections to the heliocentric hypothesis. This contest between the Ptolemic and Copernican hypotheses lasted until the nineteenth century, when knowledge of the motions of bodies in the planetary system progressed by means of celestial mechanics. Under the simpler mathematical descriptions of the motions of bodies, even the Ptolemaic system allowed the construction of a coherent theory of motion. Without celestial mechanics, the selection of the Copernican system over that of Ptolemy was a profound and far-sighted action.

2a



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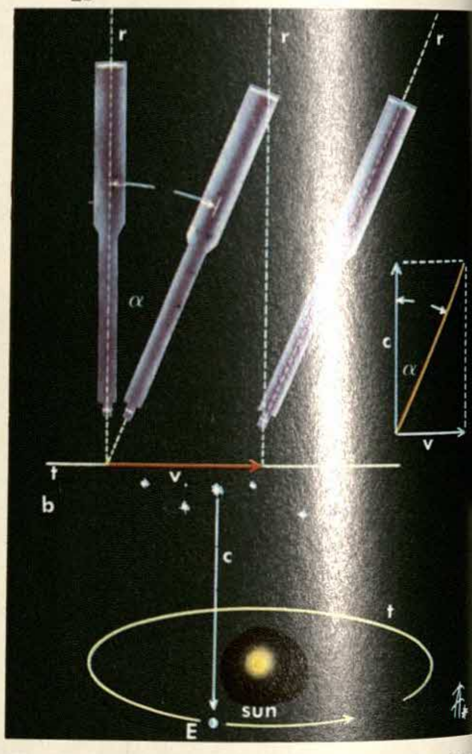

THE YEARLY ABERRATION — The revolution of the Earth in its orbit around the sun can be observed directly by telescope, taking advantage of the fact that the velocity of the Earth is not negligible when compared with the speed of light. The speed of the Earth in its orbit is about 29.79 km/sec; that of light is about 300,000 km/sec (about 186,000 mi/sec). Expressed differently, the speed of the Earth is 1/10,000 that of light.

It is a common experience to observe that drops of rain falling vertically appear from a moving vehicle to be falling at an angle. This apparent angle of the rain increases as the speed of the vehicle increases, as shown in Illustration 2a.

A terrestrial observer can note the same phenomenon in light coming from the stars if they are observed in a direction perpendicular to the plane of the Earth's orbit. Illustration 2b demonstrates that from the Earth, which moves at velocity **v** in its orbit, the light falling perpendicularly to the plane of the orbit in direction **c** will be seen as inclined.

As further demonstration, Illustration 2c shows the Earth's trajectory as **t**, the Earth's velocity in its orbit as **v**, and the starlight as a dotted line. The first vertical dotted line indicates the direction from which the light of a star comes. If the Earth were perfectly still, a telescope would have to be trained precisely along the line of the ray of light in order to observe the star. Instead, the Earth actually moves at velocity **v** and the telescope must be kept inclined in order to see the star, for the telescope is also moving at velocity **v** and must be inclined as it moves to the right in order that the whole length of the ray of light can descend the tube. The angle at which the telescope must be inclined is called the angle of yearly aberration of light for the pole of the ecliptic.

From this example, it is apparent that light coming from a direction other than perpendicular to the plane of the Earth's orbit would result in a different value. The value of an angle at which the telescope must be inclined is expressed by this relationship: tan $\alpha = v/c$, where v represents the orbital velocity of the Earth and c is the velocity of light.

When the Earth is on the opposite side of the orbit the aberration changes direction. In totality, the star is seen to describe a small circle on the celestial vault, with a diameter of about 41″ (seconds of arc). This small circle becomes an ever-narrowing ellipse, finally reducing itself to an arc as the observation point on the Earth's surface is moved from the pole of the ecliptic to the equator. In the most favorable case, therefore, $\alpha = 20.5''$.

The yearly aberration must be considered the best confirmation of the Earth's orbital movement obtainable from its surface.

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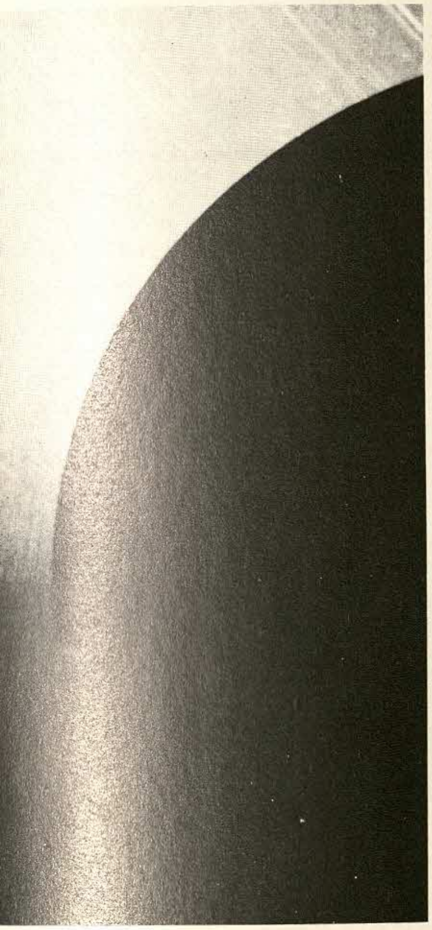

The refinement of astronomical observation by the telescope made clear the first phenomenon that constitutes direct proof of the movement of the Earth around the sun, rather than the sun around the Earth. This was the phenomenon of the aberration of light. The presence of this phenomenon is tangible proof of the Earth's motion in its orbit—and, therefore, of the validity of the heliocentric hypothesis. It is now known that an analogous observation could have been made even sooner by noting the characteristics of the impact of meteorites in the Earth's atmosphere, but this phenomenon was understood only after it had been preceded by observation of the aberration of light.

Today, observation of the Earth's motion can be assisted by space probes. It has been long evident that the Ptolemaic hypothesis, applied to the forecasting of direction and velocities of interplanetary probes, would result in the loss of all such vehicles. Thus, an experimental phase has followed the speculative phases of the problem of movements of the Earth. There are no longer doubts on the positions of celestial bodies and the motions of the Earth.

THE SECULAR PERTURBATION OF THE POLE OF THE ECLIPTIC—The pole of the Earth's orbit is that point on the celestial sphere equidistant from the great circle constituted by the terrestrial orbit (see Illustration 2b). This point is called the pole of the ecliptic. It is not immobile, but moves continuously, and it is important to observe this movement on the celestial sphere. The illustration represents the movement of this pole over a period of 200,000 sidereal years. The center of the spiral curve marks the position of the pole of the invariable plane, the plane that passes through the center of gravity of the entire planetary system and maintains its direction unvaried in space. At the moment, the inclination of the plane of the Earth's orbit is 1°35′ in relation to the invariable plane. In about 20,000 years, this inclination will be reduced to 47′; then it will gain.

It is important for astronomers to understand these movements, for the plane of the ecliptic is fundamental to many astronomical problems. For example, since the orbits of the planets are only slightly inclined to the plane of the Earth's orbit, the study of planetary motions is based on a reference system in which the fundamental direction is the axis of the ecliptic, and the great circle that of the ecliptic itself. It is, therefore, necessary to record every variation of this plane in order to carry out the necessary corrections for calculating the motions of the planets.

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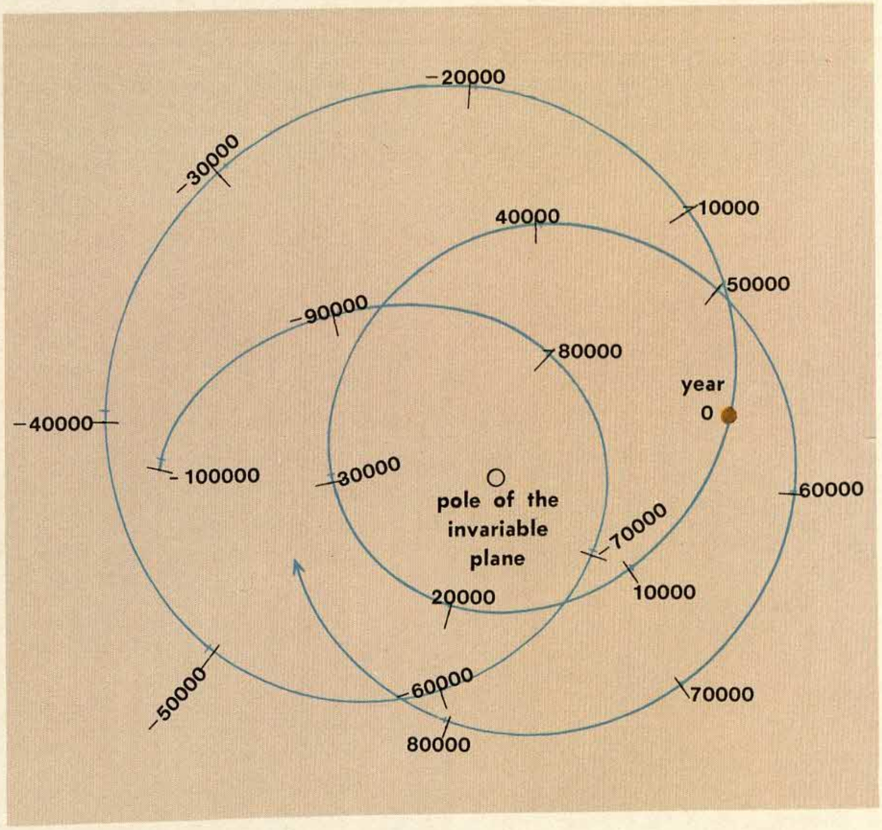

THE DAILY ROTATION—The Earth's rotation on its axis is the second most important movement to be considered. The effect of this rotation on the terrestrial observer is to show celestial bodies as if they were in motion. The photograph was made by opening the lens of a camera pointed toward the horizon and letting it remain motionless as the Earth rotated. The apparent motion of the stars to the eye of an observer is thus demonstrated.

The Earth completes one full rotation in 23 hours, 65 minutes, and 4.09 seconds (the time given is for a sidereal rotation, or the time required for a selected star to return to its initially observed position). There are various ways by which a full rotation of the Earth can be defined, as there are different ways to describe a full revolution around the sun, but the sidereal day and sidereal year are adequate means for a description of the Earth's movements.

One characteristic of the Earth's rotation that must be considered in long-term calculations is that its velocity diminishes progressively in time, although the rate of slowing is only a few seconds each century. The reason for this slowing down is the braking action of the tides caused by the attraction of the sun and moon. Although this braking action diminishes as the velocity of rotation diminishes, there is nevertheless a notable slowing down of the Earth's rotation over an astronomically long period.

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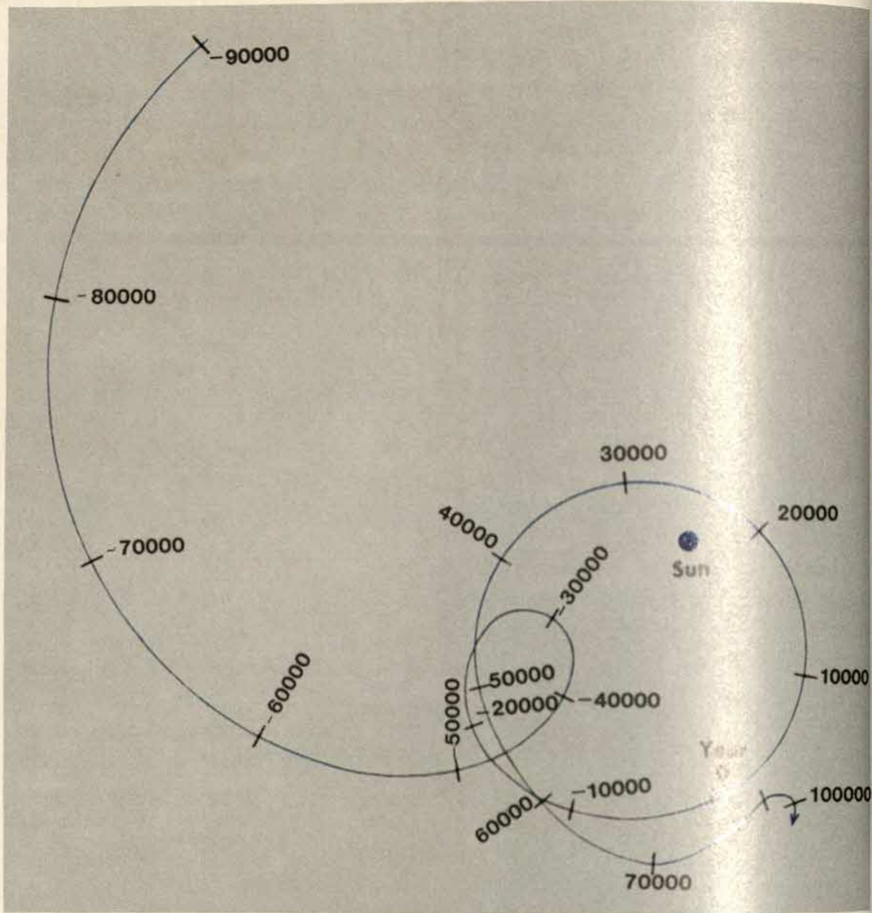


THE PERTURBATION OF THE ECCENTRICITY—The Earth's orbit is an ellipse and its axes meet in the center of the curve. The sun is not in the center of this ellipse, but is located in one of the two foci. The fourth movement of the Earth to be considered is, therefore, the variation of the center of its elliptical orbit, due to perturbations of the other planets, and the consequent variation of the eccentricity.

In this illustration, the sun is at the center of the curve shaped like a spiral. The curve is the locus of the centers of the Earth's orbit (if drawn to scale, this orbit would have a diameter of one meter). The marks on the curve indicate the passing of time in intervals of 10,000 years. The small circle shows the present position of the center of the Earth's orbit.

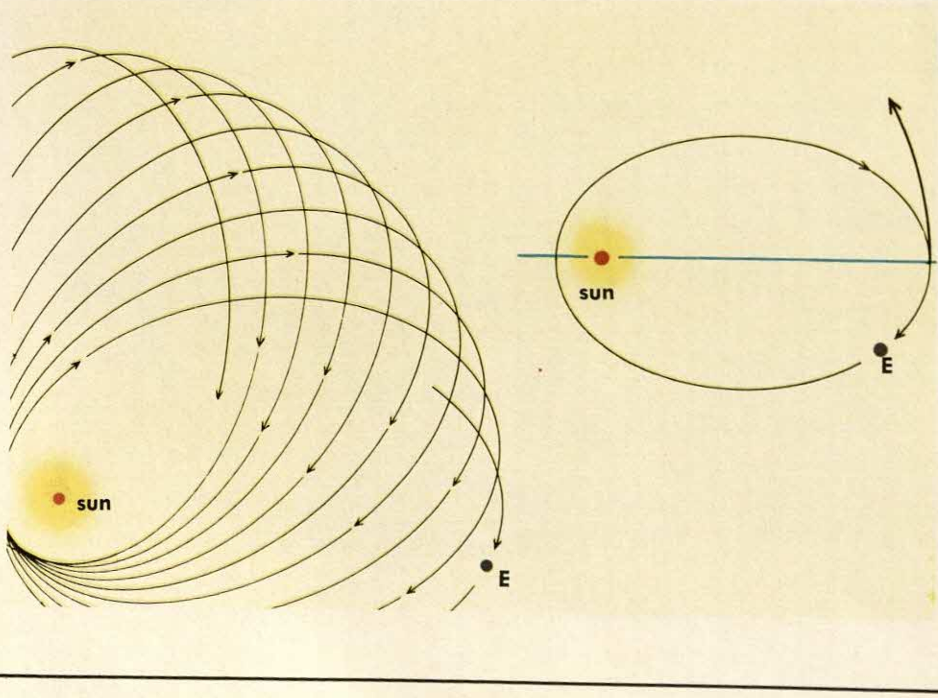
The table of variations of the eccentricity of the Earth's orbit, calculated for a period of 200,000 years, is as follows:

− 100,000	era of the maximum	0.0473
− 70,000		0.0316
− 50,000		0.0131
− 10,000		0.0187
today		0.0168
+ 10,000		0.0155
+ 23,900	minimum	0.0033
+ 50,000		0.0173
+ 70,000		0.0211
+ 100,000		0.0189

Records of the variation of eccentricity are needed to evaluate correctly not only the position in space the Earth will occupy, but also the position of the moon as it follows the Earth's movements and affects them with its own mass.

THE MOTION OF THE PERIHELION—The motion of the Earth's perihelion is another example of perturbations of the Earth's orbit. The direction in space toward which the major axis of the terrestrial orbit points is not invariable, but rotates. As a result of this movement, the Earth's orbit is not a closed curve. The other two perturbations shown in Illustrations 4 and 5 also contribute to keeping the Earth's orbit open, but their effect is less.

6

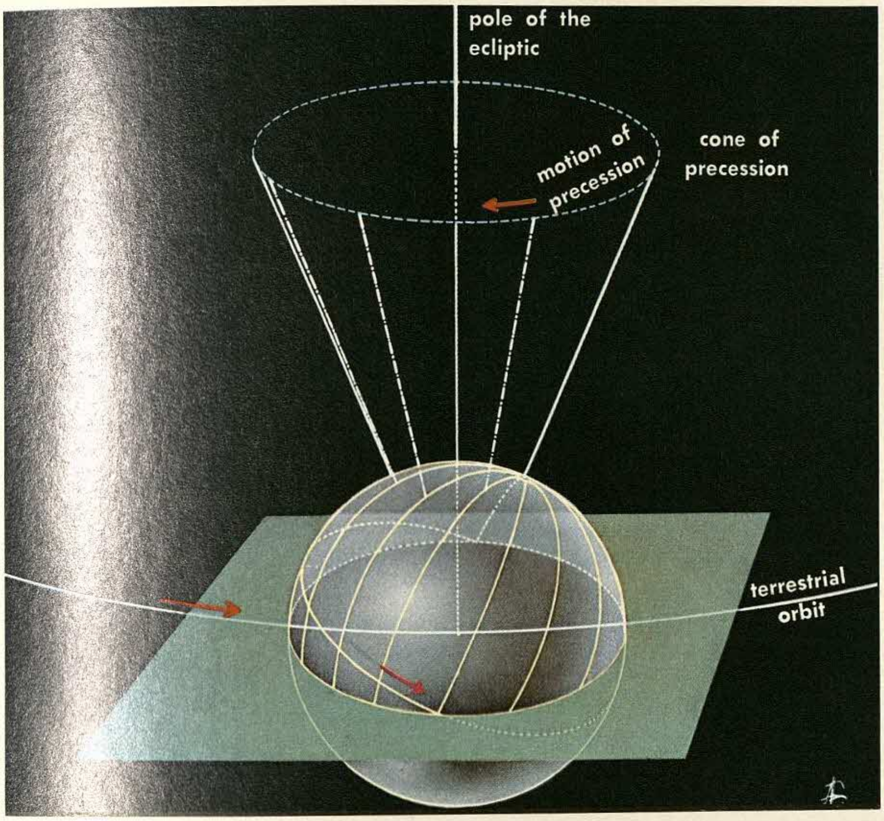


THE MOTIONS OF T[illegible] EARTH

The motions of the Earth are several and they occur simultaneously. A description of its motion is synonymous to saying in what position it will be found after a certain interval of time, when its position at a certain instant is known. To do this, it is necessary to know two important characteristics: the orbit it travels, and the law of motion that relates to this orbit.

The problem is easy to solve when the form of the orbit is simple and the law of motion is a simple one. For example, if the Earth and the sun were isolated in space, with no other planets or satellites, the form of the Earth's orbit around the sun would be an ellipse and the law of motion would be completely and fully regulated by Kepler's laws in their simplest form. Instead of this, the presence of other planets and satellites complicates the situation; it is necessary to resort to complex calculations to describe the Earth's actual motion.

a



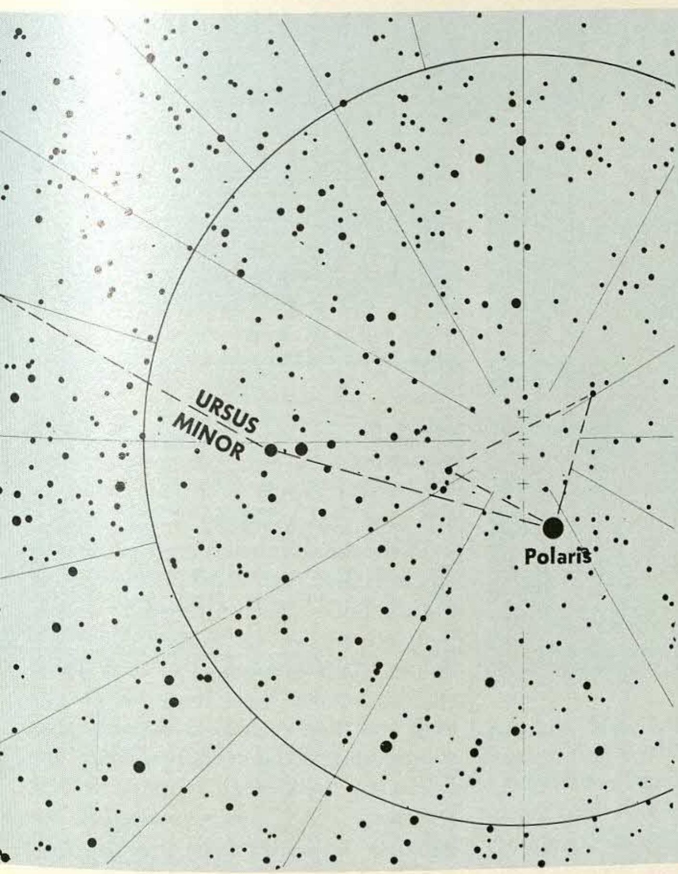
THE PRECESSION OF THE EQUINOXES—The Earth is not spherical, being slightly reduced at the poles and slightly expanded at the equator. The attraction of the sun and moon exerts a force on this equatorial swelling. Furthermore, since the Earth rotates around itself, this induced force provokes a motion of precession that causes the terrestrial axis to describe a complete cone over a period of 25,765 years. During this time the axis of the Earth's rotation points successively toward different regions of the sky. Illustration 7a shows the meaning of precession. While the Earth makes 365.25 × 25,765 rotations, its axis describes a cone whose semiaperture is 23° 26′59″. This angle, therefore, measures the distance of the celestial pole from the pole of the ecliptic—or, as an equal measurement, the inclination of the ecliptic on the celestial equator.

To the terrestrial observer, the most considerable effect of this changing position of the pole is in the variation of the stars surrounding it. The photographs in Illustrations 7b and 7b′ (next page) were taken by the same camera at a ten-year interval. Both are time photographs of about two hours' duration. The intense arc is that of Polaris; the lesser arcs were made by fainter stars, some of which are closer to the pole than Polaris. A comparison of these two photographs reveals that the faint star closest to the pole described a short arc in the first (upper) photograph, and was exactly centered on the pole in the second (lower) photograph.

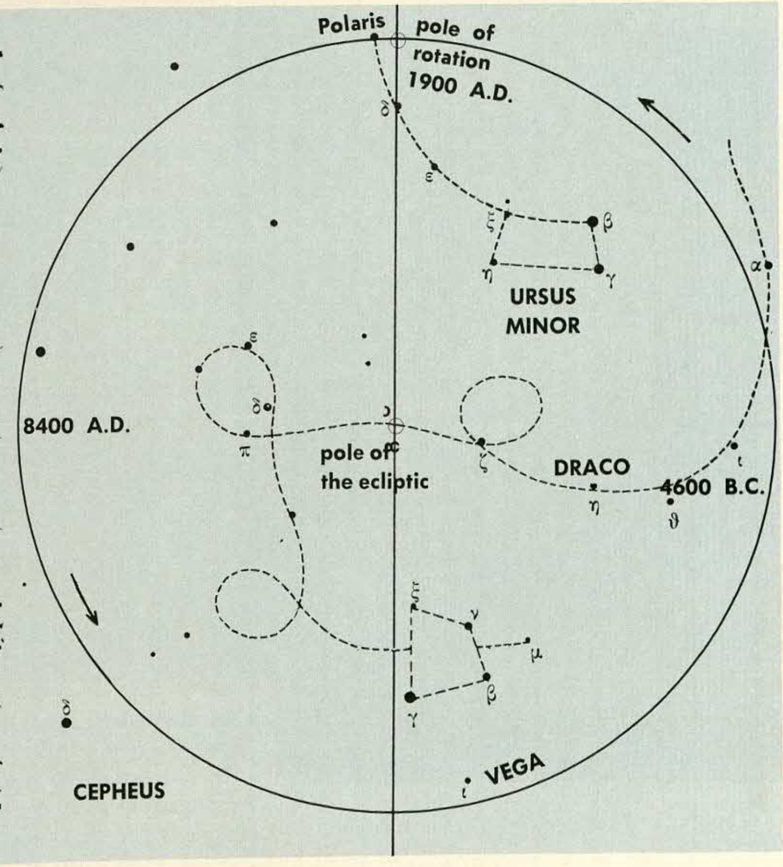
The celestial map shown in Illustration 7c gives the positions of the pole over the period of 26,000 years. Some 4,500 years ago, when the Egyptians were constructing the first pyramids, the pole star was α of the Draco constellation. In 5,600 years from the present, it will be α of Cepheus; while in 12,000 years it will be Vega. None of these stars, however, will be as close to the pole as the present pole star, Polaris.

The shifting of the equinoxes is called precession because—as shown in Illustration 7a—the motion of the terrestrial axis on the cone is a retrograde motion, as described in connection with Illustration 1, with the effect that the equinox "precedes" the Earth in its motion.

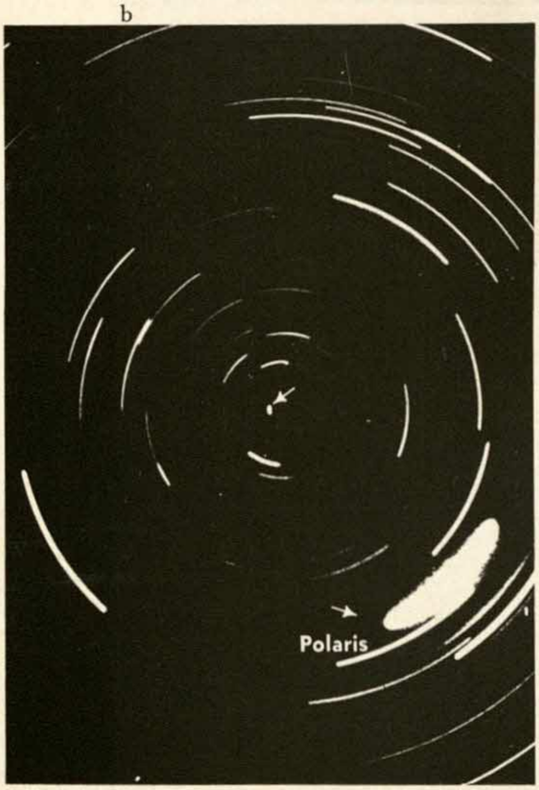
c



d

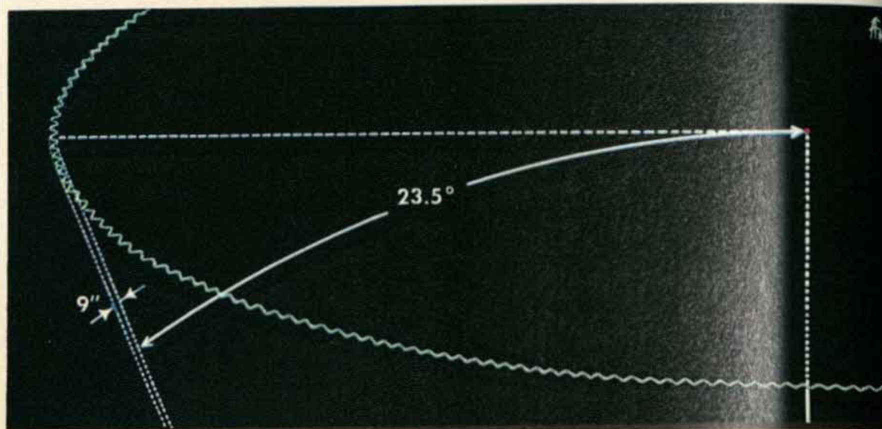


b



b′

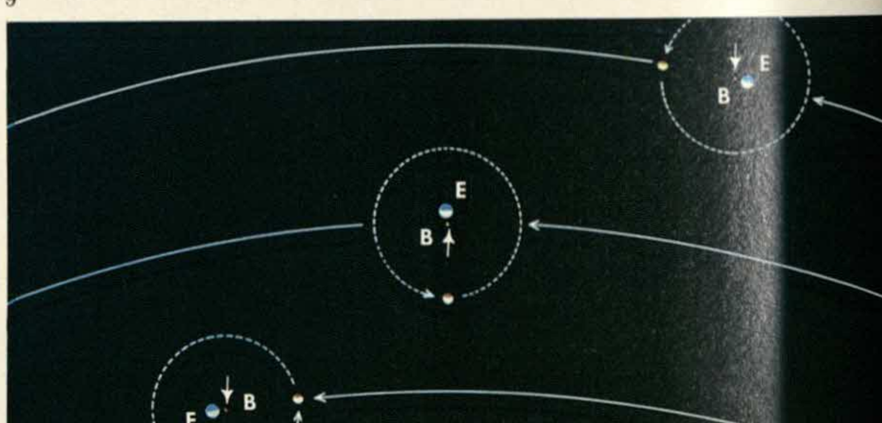
8



NUTATION—The seventh movement of the Earth is nutation, caused by the variable attraction of the moon. The moon's orbit makes some oscillations; these affect the Earth, so that the Earth's axis does not describe its cone of precession in an exact manner, but also with some oscillations.

The illustration shows the relationship between precession and nutation. The amplitude of the oscillation is about 9" of arc, the cycle about 18 years and 8 months. There are about 1,420 oscillations of nutations every 25,765 years, considering only the principal nutations.

9

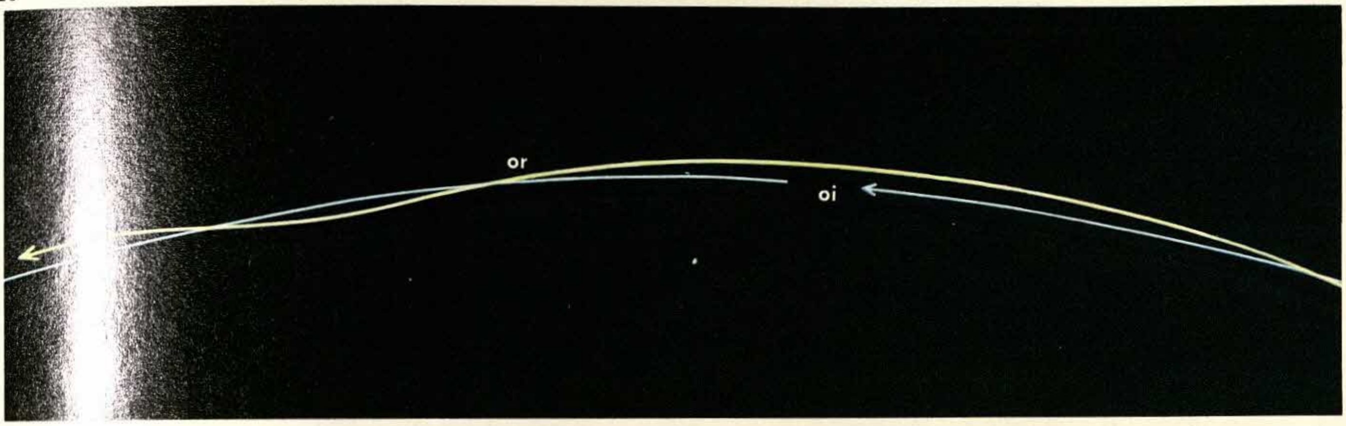


THE MOTION OF THE BARYCENTER—It is not possible to know the position of the Earth in its orbit unless the equivalent position of the moon is also determined. The barycenter of the Earth-moon system (not the Earth alone) moves along the terrestrial orbit in strict accordance with Kepler's laws. The top orbit shown in the illustration describes the Earth, the barycenter **B** of the Earth-moon system, and the moon in the last quarter. The center orbit shows the moon passed to its new phase and the Earth advanced (left) in its direction of orbit. The bottom orbit shows the Earth farther advanced, with the moon reaching the phase of its first quarter, from which point it slows down. Such is the eighth movement of the Earth.

This complex problem, however, can be simplified by making a representation by resolution. The motion of the Earth results from the sum of many elementary movements, each one produced by its own cause. Simplification of these many movements begins with a determination of all the components into which the act of the Earth's motion can be resolved. The best-known ones are rotation, which produces the alternation of day and night; and revolution, which brings the Earth around the sun during the year and produces the changing of the night sky. A third movement is the variation in the orientation of the Earth's axis, which determines the precession of the equinoxes. A fourth movement is the translation of the planetary system, drawn by the motion of the sun as it travels within the Galaxy.

To the four elementary movements described above can be added seven other principal ones. Some of these, of a complex nature, can be broken down into simpler considerations. The accompanying illustrations show these eleven motions and their reciprocal importance in contributing to the overall motion of the Earth. It is the kinematic aspects of these movements that are of increasing importance, rather than the way in which men have defined and classified them.

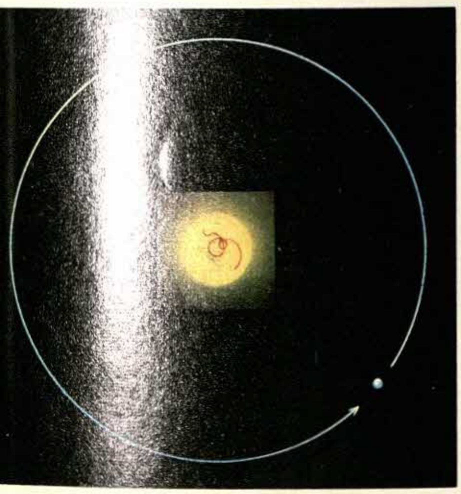
10



THE PERTURBATIONS—The attraction of the planet Jupiter, with its great size and weight, and of Venus because of its closeness to the Earth, cause a periodic shifting of the Earth from its ideal orbit **oi.** The real orbit **or** reflects these influences of our sister planets. This ninth movement of the Earth, like others, can be resolved into many components.

THE WANDERING OF THE PLANETARY BARYCENTER—The tenth movement of the Earth is the result of the fact that the Earth does not revolve around the sun with that star in the focus of its ellipse, but with the barycenter of the planetary system as its focus. The barycenter of the system may fall within the solar sphere, but never coincides with the sun's center and can be a considerable distance from it. The planetary center can be determined by calculation based on the positions of the various planets and their satellites.

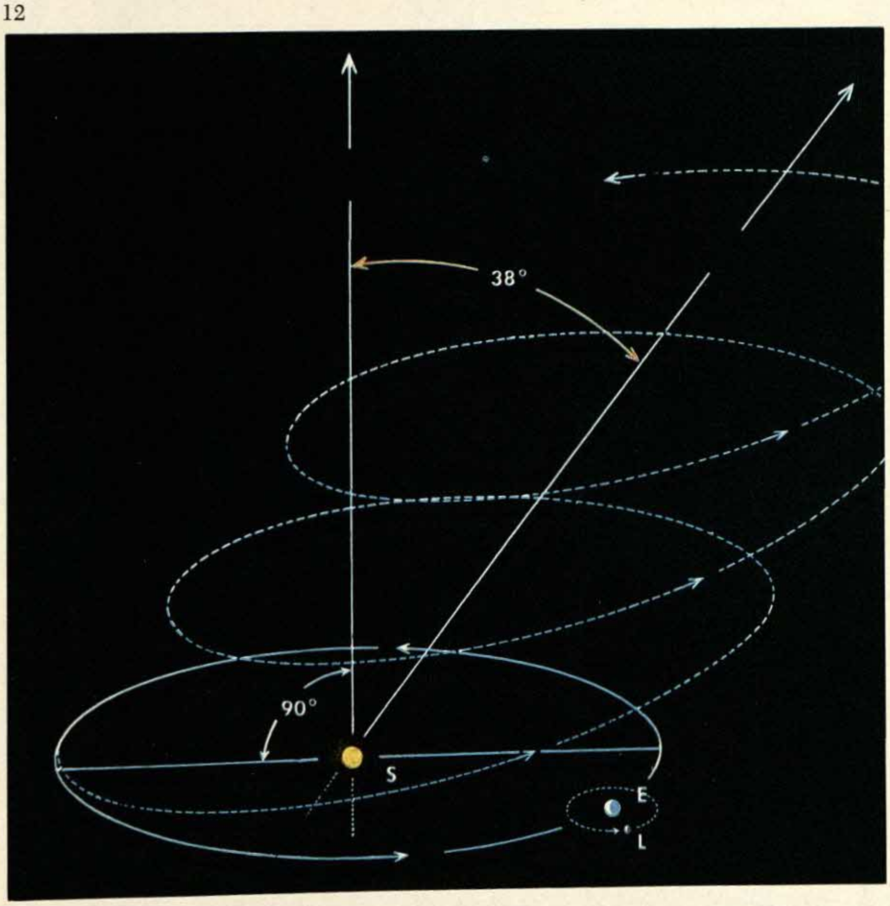
11



The illustration shows the movement of the planetary barycenter around the solar center; this barycenter, not the solar center, is the focus of the Earth's orbit. Both the sun and the movement of the barycenter within it are enlarged forty times over the Earth orbit shown.

TRANSLATION—Observations and measurements carried out over centuries have shown that the sun and its planetary system move in space toward a point known as the apex of solar motion. The point is in the direction of the constellation Vega. This movement of the sun toward a distant point in space, at a speed of about 20 km/sec (about 12.5 mi/sec), is also one of the most important movements of the Earth. The illustration shows the consequence of this movement: the Earth's orbit describes a cylindrical spiral around the sun.

12



THE STUDY OF MARS | history of observations of a neighboring planet

The Earth is the third planet in distance from the sun; the fourth planet in distance is Mars. This planet has been observed since ancient times, for it is an extremely bright object in the sky, with a distinctive reddish color. Its orbit carries it almost as near to the Earth as Venus, the second planet in distance from the sun; but when Mars is at the far end of its orbit (in conjunction with the sun), it can be five times more distant than Venus. Mars has the luminosity of a star of +1.6 magnitude when it is farthest from the Earth; as it approaches the Earth, the magnitude increases to between −1.1 and −2.8. (Negative magnitudes are brighter than positive magnitudes.) In other words, Mars at its dimmest is a little brighter than Polaris, the Pole Star; at its brightest, Mars compares with Sirius and may even rival Jupiter and outshine all the stars in the sky. More is known about Mars than about any other body in the solar system with the exception of the moon and the Earth.

1

EARLY OBSERVATIONS

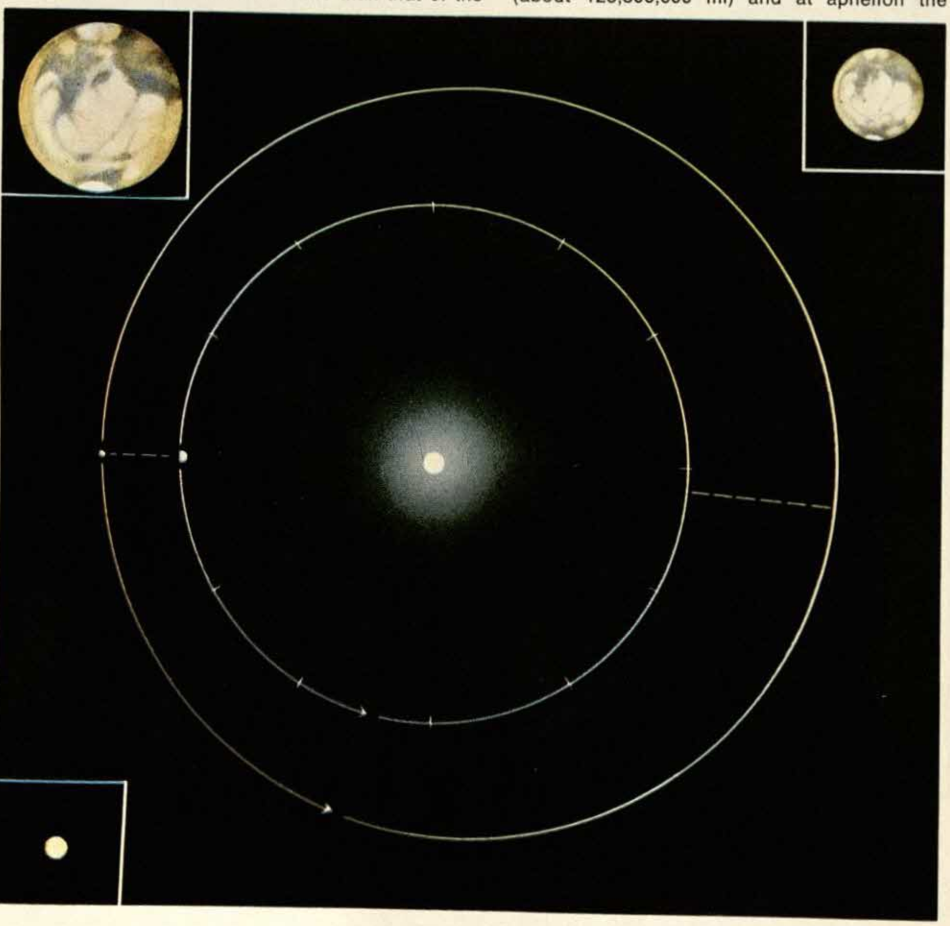
At the end of the sixteenth century, at the height of the controversy over the validity of the Ptolemaic and Copernican concepts of the solar system, the Danish astronomer Tycho Brahe made the first exact observations of the motions of any planet—Mars. The scientists of the time, disputing whether the sun or the Earth was the center of the universe, preferred to ignore data that supported one theory or the other, and Brahe himself remained aloof from the discussion. However, he constructed instruments—chronometers and goniometers with hairline finders (the telescope had not yet been invented)—with which he could measure precisely the motions of celestial bodies.

Brahe established for the first time the positions occupied by Mars on two successive nights, and noted the exact times when the planet appeared in these positions. His observations were so accurate that they enabled Brahe's assistant and successor, Johannes Kepler, to conclude that planets moved in elliptical rather than circular orbits, as Copernicus had believed. Brahe's observations, however, were limited to the mechanics of the movements of Mars; observations of the planet's surface were not made until Galileo's telescope had been largely modified and perfected.

PHOTOGRAPHIC OBSERVATIONS

The Yerkes Observatory in Wisconsin has the world's largest refracting telescope, with an objective lens about 100 cm (about 40 in.) in diameter and a focal length of about 19 m (about 62 ft). With the use of this lens, the real image of the planet registers photographically at a diameter of 2 to 2.5 mm (almost 0.1 in.), depending on whether the opposition of the planet is less or more favorable. Because of the long focal length of the lens, the exposure must continue for a considerable fraction of a second even

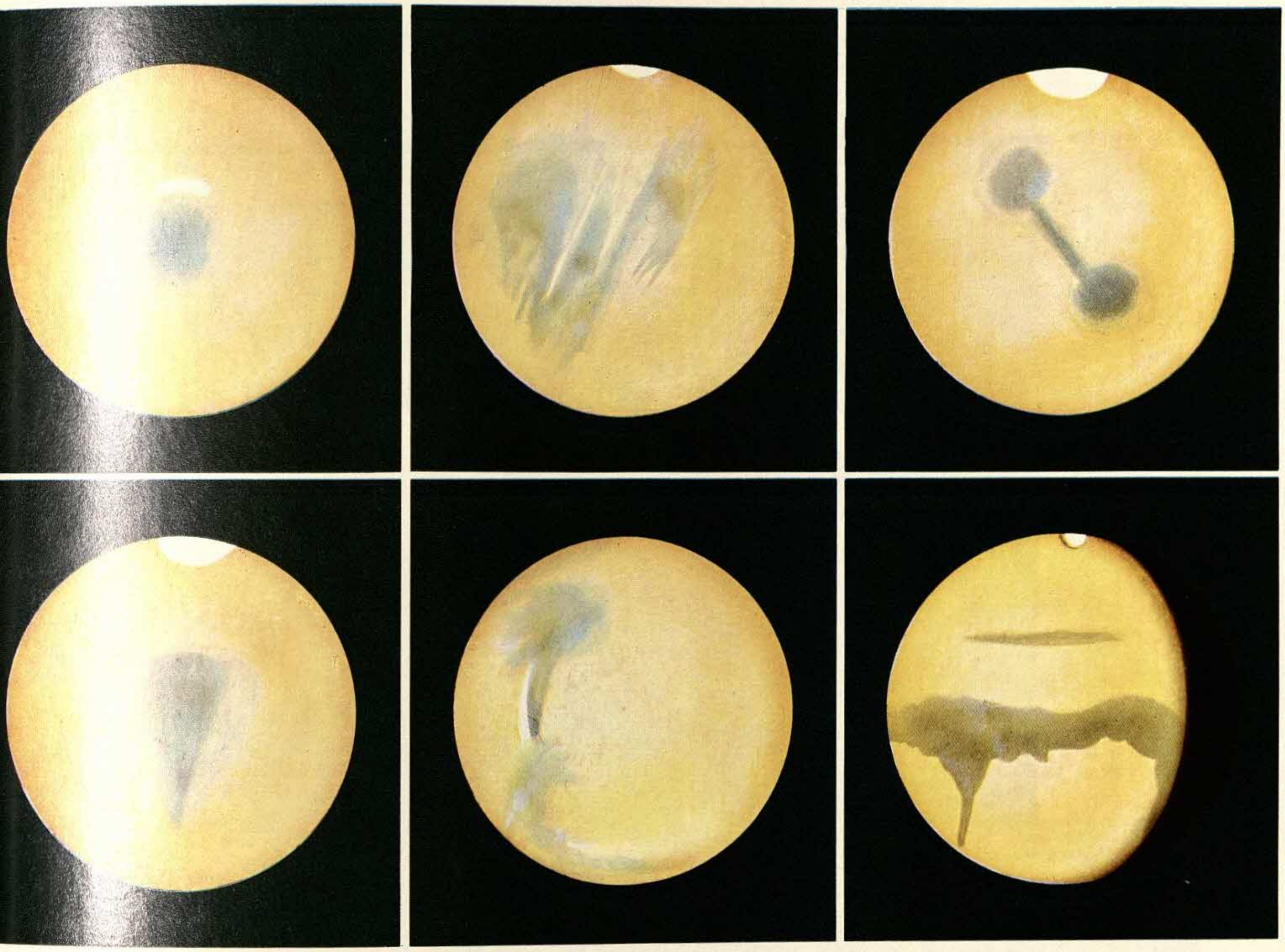
THE ORBIT OF MARS—The planet Mars is somewhat difficult to observe because of its orbit in relation to that of the Earth. The orbit of Mars is inclined only 1°51′ to that of the Earth, but it is more eccentric than that of the Earth. Its mean distance from the sun is 227,400,000 km (about 141,300,000 mi), but the actual distance at perihelion (its nearest approach to the sun) may be only 206,500,000 km (about 128,300,000 mi) and at aphelion the distance may be as much as 249,100,000 km (154,800,000 mi).



The Earth's orbit around the sun is inside that of Mars and is only slightly eccentric. During their respective orbits the two planets may arrive at points that are relatively close or distant; the former positions are designated as favorable—that is, they are favorable for observation—whereas the times when the planets are far apart are for the same reason designated as unfavorable. Mars and Earth may, under favorable conditions, be within 55,795,000 km (about 34,670,000 mi) of each other; under unfavorable conditions they may be 398,950,000 km (about 247,900,000 mi) apart. When Mars passes closest to Earth, as is seen in the illustration, it is on the opposite side of the sun, and therefore is described as in opposition. When it is farthest away, the sun is between Earth and Mars, and the latter is said to be in conjunction.

The planet can be in opposition and still be relatively close to Earth (during perihelion, shown by the broken line between orbits at left), or relatively distant (during aphelion, shown by the broken line between orbits at right); the former is called favorable opposition, while the latter is called unfavorable opposition. During favorable opposition the diameter of the planet may appear to be about 25 seconds of arc across; this will be reduced during an unfavorable opposition to about 13″, and during an unfavorable conjunction to only 3.5″. Even a month before or after the moment of opposition reduces the distance between the planets measurably, and thus only a few nights are available for the most favorable observation. Inasmuch as some nights have better weather conditions than others, and because the sky is clearer during some hours than during others, each opposition affords only a few hours of prime time for observation. Moreover, periods of opposition recur only once in about every two and a half years; and favorable oppositions only once in about 15 to 17 years. The next was expected in 1971.

2a 2b 2c



2d 2e 2f

THE FIRST TELESCOPIC OBSERVATIONS OF MARS—At a distance of 25 cm (about 10 in.) the human eye can distinguish two points that are one minute of angle apart, that is, separated by about 0.01 mm (0.0004 in.), a quarter of the thickness of a human hair. Galileo's telescope resolved images at a distance apart of 10″ of arc, six times more precisely than the human eye. This greater resolution (apart from the magnification used) was enough to show the topography of the moon, the spots on the sun, the phases of Venus, and the ring of Saturn. In 1630, two decades after Galileo's telescope, instruments with a resolution of 3″ of arc were built. These telescopes were powerful enough to distinguish the surface features of the planets. One astronomer saw a spot in the center of the disk of Mars (he called it "the pill"), but this was the only surface feature he saw; the polar cap, the most important feature, was not visible to him. The polar caps were first observed in 1670 by the Dutch astronomer Christiaan Huygens, who had built a telescope with a resolving power of 2″ of arc, 30 times greater than the resolving power of the human eye.

In 1680 Jean-Dominique Cassini, a French astronomer, using a telescope with a resolving power of 1″ of arc, found smaller details on the surface of the planet. These observations still did not provide enough information for a study of the planet. No practical progress in astronomical optics was made in the eighteenth century, although theoretical optics had discovered how to construct instruments with greater resolving power. In particular, it was known that resolving power was directly proportional to the diameter of the lens, and the surface characteristics of such lenses were precisely computed. At the beginning of the nineteenth century the invention of the achromatic lens opened the way to the design of telescopes with a resolving power of 0.5″, and by the end of the century, less than 0.25″. These conditions made it possible to see the permanent features of the planet and to draw detailed maps of its surface.

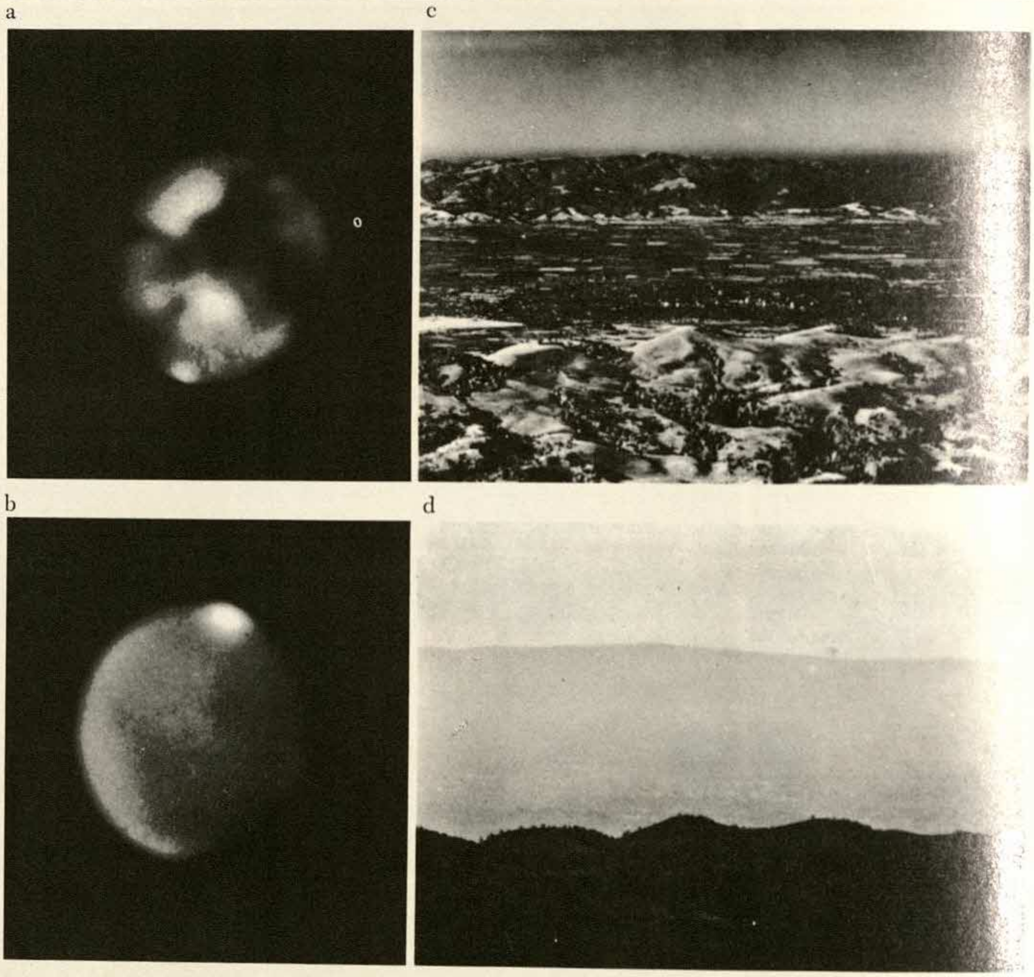
The maps shown illustrate the appearance of Mars according to some astronomers over a period of several centuries: 2a, Fontana in 1636; 2b, Huygens in 1659; 2c, Cassini in 1666; 2d, Giacomo Filippo Maraldi in 1719; 2e, Sir William Herschel in 1780; and 2f, J. H. Schröter in 1798.

when a highly sensitive film is used. During the exposure period the image is affected by atmospheric turbulence and, therefore, appears more blurred than under direct observation by the eye, which is less distracted by minor distortions of this kind. Nevertheless, some excellent photographs have been obtained.

MOTION PICTURE PHOTOGRAPHY

At the beginning of the twentieth century many large reflecting telescopes were constructed. These were not considered suitable for observing the planets, particularly Mars, because their huge mirrors, which are used as objective lenses, reflect much of the perturbation of the Earth's atmosphere. However, these telescopes do gather a large amount

3



FILTER PHOTOGRAPHY—An advance that in certain cases makes photography superior to visual telescopic observation was the development of optical filters, which pass radiations of specific frequencies. If a planet is photographed through filters that pass only the violet and ultraviolet radiations of the spectrum, the photographic image shows only those details of the planet that reflect violet and ultraviolet light—in the case of Mars, particularly the clouds of the thin atmosphere. Therefore, ultraviolet photographs of Mars are especially useful in studying the meteorology of the planet. On the other hand, infrared filters make it possible to photograph the radiation from the planet's surface—radiation that penetrates the misty, turbulent atmosphere without being absorbed.

These photographs illustrate the use of filters in photography. When the same landscape is photographed through an infrared and an ultraviolet filter, the results appear in Illustration 3c and 3d; similarly, when Mars is photographed through an infrared and an ultraviolet filter (Illustrations 3a and 3b), the former reveals many surface features, while the latter reveals mostly mist and clouds.

of light, and their focal length—less than five times the mirror diameter, as compared with as much as 20 times the focal length in some refracting telescopes—permits photographic exposure time of as little as a few hundredths of a second when the subject is a body as bright as Mars. Thus it is possible to take long sequences of thousands of frames of photographs with a motion picture camera; among these thousands a few are likely to have been taken during the rare moments of atmospheric calm. A few such photographs can be selected, producing some highly detailed and clear photographs of the surface of Mars, such as those taken with the 200-in. Mount Palomar telescope.

SPACECRAFT PHOTOGRAPHY

In November 1964 Mariner IV was launched from Cape Kennedy. In July 1965 it approached within 6,200 miles of the surface of Mars. During the flyby, 22 telescopic pictures were taken of the planet. These photographs were relayed to Earth by the spacecraft telemetry systems. The pictures show craters similar to those on the moon. The craters range in size from 2.8 to 170 km (1.7 to 110 mi) in diameter.

In 1969 Mariners VI and VII successfully relayed additional photographs from the vicinity of Mars. These photographs were similar to those from Mariner IV.

Mariners VI and VII each passed only about 2,000 miles from the surface of Mars. They took a total of about 200 television pictures. Experiments performed during the two space journeys confirmed the extreme tenuousness of the Martian atmosphere; the pressure on the surface is only about 1 percent of the Earth's surface pressure.

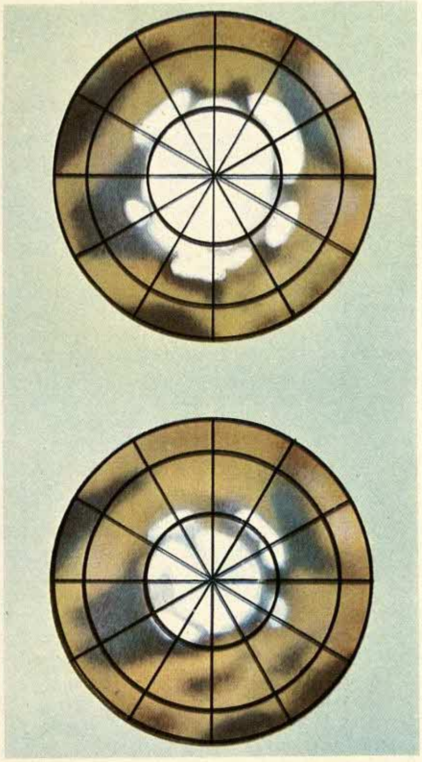
THE TOPOGRAPHY OF MARS | the geography of another planet

Within the past 100 years, several surface maps of Mars have been drawn. The surface of this planet has many permanent features related to the physical nature of the terrain rather than to atmospheric variables. Each of several scientists who mapped the surface of Mars adopted a nomenclature for the features he observed, and it was not until some time later that the International Astronomical Union standardized the names, using mainly those proposed by the Italian astronomer Giovanni Schiaparelli. The term *mare* (Latin for "sea") occurs with great frequency as it does on maps of the moon, for it was thought that these Martian areas contained water. Space exploration is eliminating uncertainties from the study of Mars.

THE MAP OF MARS

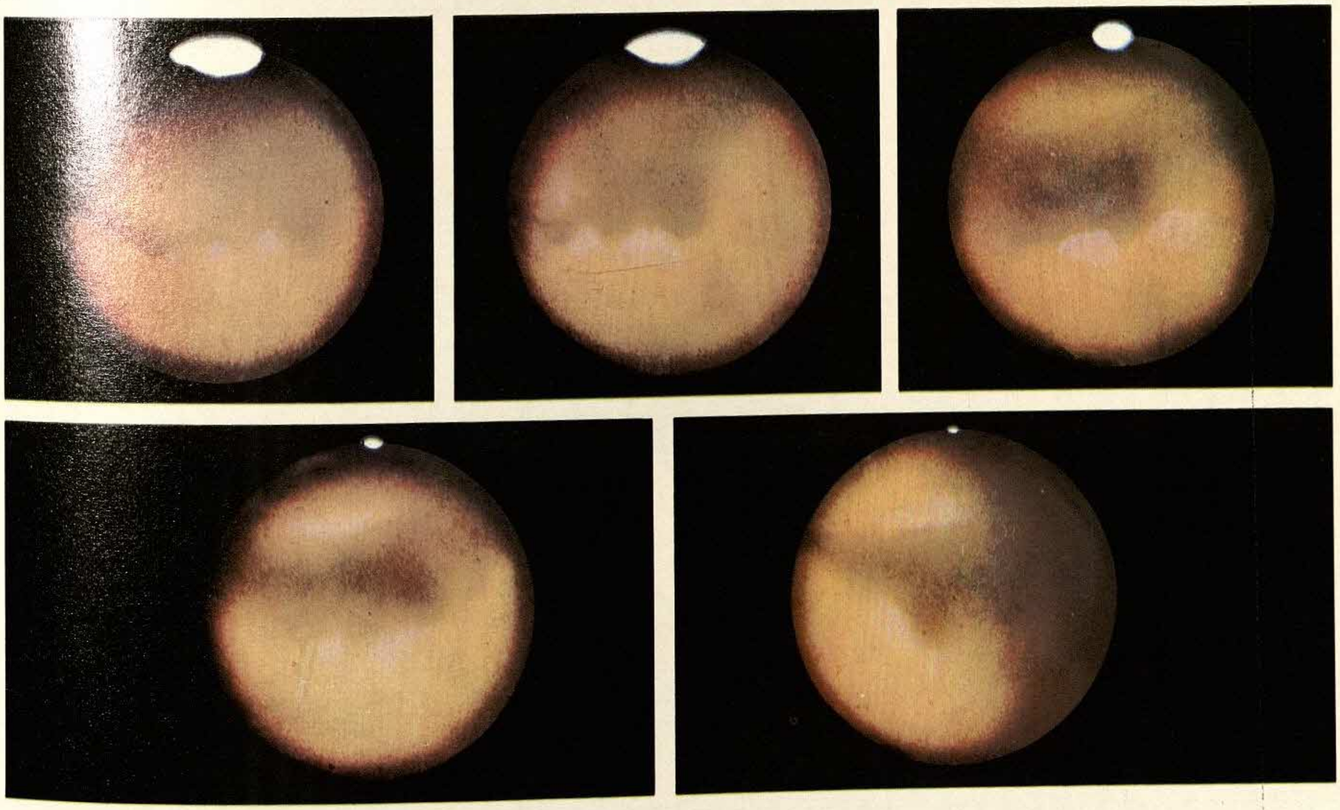
Much sharper contrasts appear on a map of Mars than on the image of the planet as seen through a telescope. Amateur observers, unaware of this, often are discouraged because they cannot see the planet as sharply through a telescope as it appears in maps in which the intensity of the colors is usually heightened. When actually viewed, areas such as Ceraunius and Deuteronilus are even less distinctive than would appear from the markings on the map (Illustration 2, at +30° lat 90° long and +40° lat 0° long respectively). They would hardly be perceptible, in fact, with the best telescopes. The features shown on the map cannot be seen during a single night through any

1b



THE POLAR CAP—The five photographs below (Illustration 1a), selected from photographs of Mars taken over consecutive periods, show the progressive diminution of the polar cap with the advance of summer and the simultaneous gradual appearance of areas of dark color in the tropical zones. The two drawings in Illustration 1b show the polar cap as it would appear from above the planet's axis.

1a



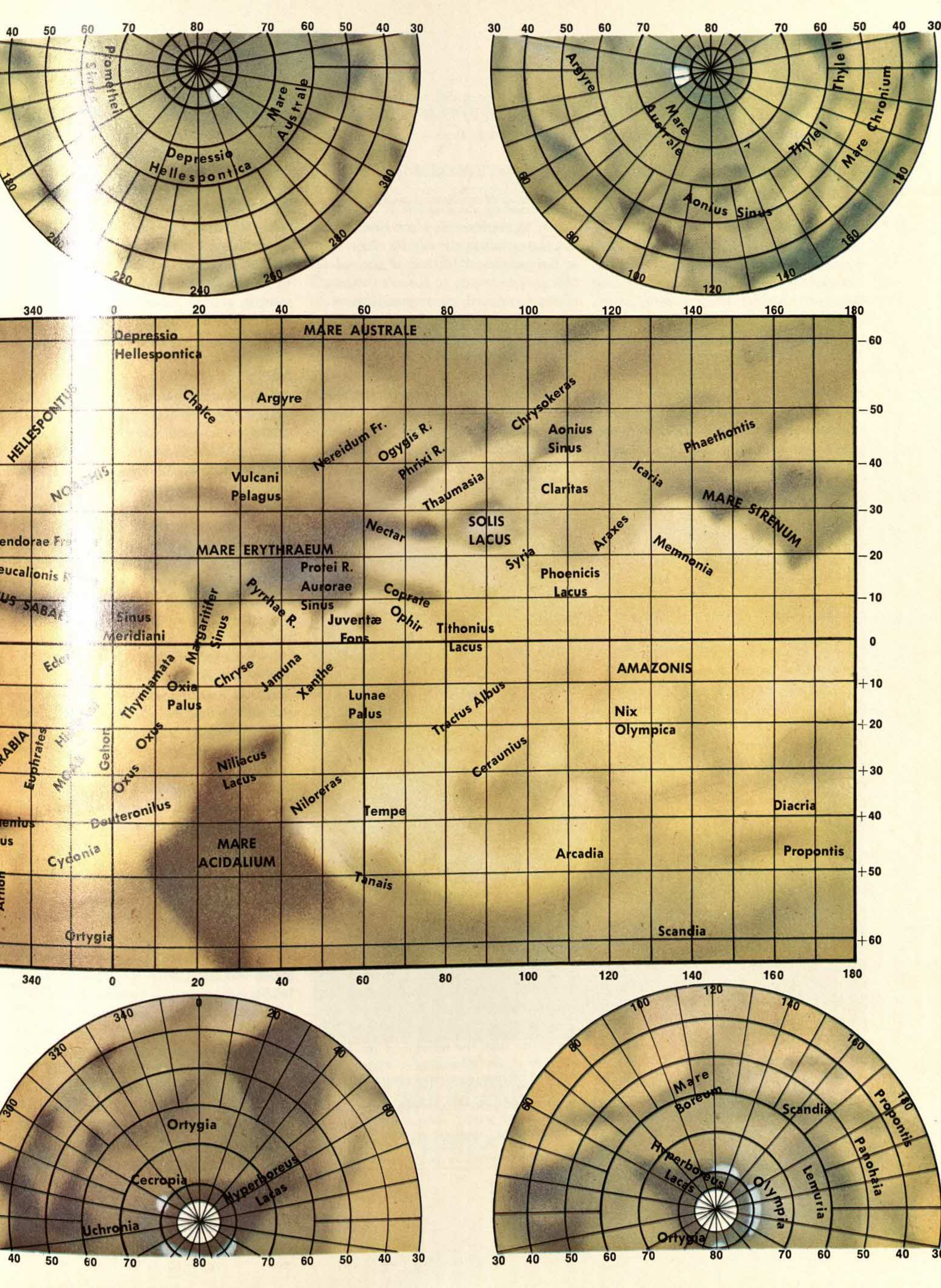
THE MAP OF MARS—These are maps of Mars: a Mercator projection (the central rectangle) of the equatorial and temperate latitudes; and the polar regions. They are drawings; no photograph can reproduce the delicate shades of color of the planet's surface or include all the details seen through a number of telescopes. The study of the surface of the planet is called "areography" because the Greek name of Mars was Ares.

Observations of many astronomers over the decades provided the data for this composite map. These astronomers are not only competent observers; they must also be able to record what they have seen. During the course of one night an astronomer might record only a hundredth part of what appears on this map, because his vision is impeded by the Earth's atmosphere, the atmosphere of Mars, and the limitation imposed by the rotation of Mars, which leaves only a few hours to observe a detail in the center of the face of the planet. When this detail shifts to the horizon, it becomes indistinct and blurred.

Moreover, not more than 40 nights every two years are favorable for the observation of Mars. Observations made during these nights are compiled by the astronomers in a series of maps and drawings that are then analyzed; all the details that have appeared during the nights of observation in a single region are collated and drawn as a composite, usually in water colors. A special commission of the International Astronomical Union then collated all the studies prepared by the astronomers to construct a collation of the collations—the maps in this illustration.

The nomenclature appearing on the map originated with the Italian astronomer Giovanni Schiaparelli, although many astronomers have contributed names to the features of Martian areography. Many regions whose off-blue color intensifies during the hot season, when the polar caps retreat, have been designated as maria.

A new era of Martian exploration opened with the approach from space, with spacecraft photographing the planet from distances of about 9,650 km or about 6,000 mi (Mariner 4 in 1965) and slightly more than 3,370 km or 2,100 mi (Mariners 6 and 7 in 1969). These photographs have revealed that the planet's surface is, like that of the moon, marked with numerous craters. Infrared radiometers aboard Mariner 7 disclosed temperatures indicating that the polar caps probably contained more frozen carbon dioxide (dry ice) than frozen water (ice). Precise information of the configuration of Martian topography and the causes of the planet's coloration awaits further exploration, not only by additional launching of unmanned—and perhaps manned—spacecraft to reach Mars, but also by establishing a telescope either on the moon or on an orbiting observatory outside the opacity and turbulence of the Earth's atmosphere.


Promethei Sinus
Mare Australe
Depressio Hellespontica
Argyre
Mare Australe
Thyle II
Thyle I
Mare Chronium
Aonius Sinus
MARE AUSTRALE
Depressio Hellespontica
HELLESPONTUS
Chalce
Argyre
Chrysokeras
Aonius Sinus
Nereidum Fr.
Ogygis R.
Phrixi R.
Phaethontis
Icaria
Vulcani Pelagus
Thaumasia
Claritas
MARE SIRENUM
Nectar
SOLIS LACUS
Araxes
Memnonia
MARE ERYTHRAEUM
Protei R.
Aurorae Sinus
Syria
Phoenicis Lacus
Pyrrhae R.
Coprate
Margaritifer Sinus
Sinus Meridiani
Juventæ Fons
Ophir
Tithonius Lacus
Chryse
Jamuna
Xanthe
AMAZONIS
Thymiamata
Oxia Palus
Lunae Palus
Tractus Albus
Nix Olympica
Euphrates
Oxus
Gehon
Niliacus Lacus
Ceraunius
Nilokeras
Tempe
Diacria
Deuteronilus
Cydonia
MARE ACIDALIUM
Arcadia
Propontis
Tanais
Ortygia
Scandia
Ortygia
Cecropia
Hyperboreus Lacus
Uchronia
Mare Boreum
Scandia
Propontis
Hyperboreus Lacus
Panchaia
Lemuria
Olympia
Ortygia

telescope, for the map is really a composite of a great many observations.

The most recognizable features on the surface of Mars are the polar caps, two white areas near the poles that increase and diminish seasonally. Inasmuch as Mars rotates around an axis inclined at about 24 degrees from its rotational plane (almost comparable to the Earth), its seasons resemble those of the Earth, although they are longer because the Martian year lasts for 687 terrestrial days. The intensity of the seasons on Mars differs in the two hemispheres, however. The southern hemisphere of the planet is much closer to the sun in summer than in winter, and so is extremely hot in summer and extremely cold in winter; whereas in the northern hemisphere the seasons are reversed. It was long believed that the polar caps were condensations of water in the form of ice, snow, or even dense fog and clouds, and that their spreading indicated the degree of coldness in the polar areas. As the hot season advances in a hemisphere, the cap diminishes; when cold weather arrives, the cap spreads. The southern polar cap sometimes disappears entirely during the summer, but in winter it extends all the way to the temperate zone; whereas the northern cap never disappears entirely, even during the summer (its minimum diameter is about 300 km or about 185 mi), and in winter it extends for a distance about three fourths that of the southern cap. These variations are caused by climatic conditions resulting from the positions of the caps and the distances from the sun.

The resemblance of these caps to terrestrial polar ice caps suggested that the caps on Mars were composed mostly of ice. They appeared to have a greater area when photographed with ultraviolet filters, which admit light from the atmospheric mist, than when photographed with infrared filters, which admit only the reflections from the terrain, presumably ice or snow. Consequently, it can be assumed that the caps seen in visible light are composed partly of clouds. As the caps retreat, the edges break off and white fragments, detached from the main mass, remain stationary. This suggests the presence of mountainous terrain. Given the thin atmosphere of Mars, elevations of only a few hundred meters would produce a difference in temperature sufficient to keep the ice or frost frozen for some time.

THE ROTATION OF MARS

The period of the rotation of Mars is 24 hours, 37 minutes, 58 seconds—a precise calculation made possible by observation of the permanent features of its surface. It is only necessary to observe the length of time required for a given feature to rotate 20 or 30 times to calculate provisionally the period of a single rotation; any error in determining the exact instant at which that feature completes a single rotation is thus spread over a larger number of rotations, giving a result that may be considered reasonably precise but scientifically still provisional. This result is then compared with the records of other observers who have, since the early eighteenth century, carefully noted and left records of the appearance of certain features on their charts. Inasmuch as time was measured with great accuracy even in those days, any errors in observation are spread over hundreds of thousands of rotations, giving an extremely exact result.

This period of a single rotation—actually, the length of a Martian day—is almost the same as that of a terrestrial day; therefore, a feature on the planet's surface observed one night will be found the following night at almost the same place. (Because the Martian day is slightly longer than an Earth day, the feature will seem to have slipped back by about 9°.) After 20 days, with a turn of 180°, a feature appearing at that location on the planet will be almost exactly opposite the feature observed on the first night.

The rotation of the planet results in a slight flattening at the poles—a flattening exceeding that of the Earth (1/190) even though the period of rotation is longer. The explanation of this greater flattening, measurable by telescope but not apparent to the eye, is that the interior of Mars is more homogeneous and less dense than the interior of the Earth.

THE GENERAL SURFACE APPEARANCE OF MARS

Except for the white polar caps, Mars is orange ochre-red in color, with patches over three eighths of the surface tending toward blue-gray or green. The orange surface retains its color permanently, and seems to be very smooth; if there were mountains a few thousand meters high, they would cast shadows that could easily be seen, especially at the terminators (the line between light and dark, or day and night, on the face of the planet). The blue-gray and green areas, however, change in intensity with the seasons, and are usually less bright than the rest of the surface. As the polar cap of a hemisphere retreats, the blue-gray and green regions are more intense in their color.

This characteristic as well as the color suggested the use of the term mare (plural, maria), which is inappropriate for a number of reasons. First, if these were actually seas, they would reflect the sun under favorable circumstances, but no such reflection has ever been observed despite special studies in this direction. Second, the color in these regions varies in intensity from place to place, which might suggest shallow lakes or swamps but not seas such as those on Earth. Finally, even in the same mare, variations of color occur periodically and also at random, which would not be likely if these were deep water-filled depressions.

In any case, the periodic variation in the intensity of the colors, synchronized with the seasons, suggests that there may be a movement of water over the surface of the planet from the poles toward the equator; and the possibility of vegetation in the more darkly colored regions seems likely. These observations have not been supported by sufficient information to justify a final plausible hypothesis to explain the phenomena; the information gathered through the use of spacecraft can be expected to provide more useful data concerning the surface of the planet.

The U.S. National Aeronautics and Space Administration planned to soft-land a complex instrument payload on Mars in 1975. The spacecraft was expected to include wide-ranging television equipment, a gas chromatograph mass spectrometer for the identification of organic molecules in the Martian soil, a device for the detection of water bound in rock or other solids, and a set of meteorological indicators. A retro-rocket landing was expected to be employed.

LIFE ON MARS | the environment of a neighboring planet

Scientists and science enthusiasts have long been fascinated by the possibility that the similarity between the features of Earth and its planetary neighbor Mars might indicate that life exists on Mars. Certain individuals have contributed money to finance the construction of powerful telescopes to study the details of earlier observations. One European benefactor actually offered a prize of 100,000 marks for proof of communications with the inhabitants of any planet other than Mars, possibly assuming that communications with Mars was a feat so probable that no prize was necessary. Many astronomers have observed markings on Mars that seemed so similar to man-made constructions that they might be attributed to intelligent beings. This point of view is no longer seriously advanced, but it remains of great popular interest and was long a staple of science fiction.

THE "CANALS" OF MARS

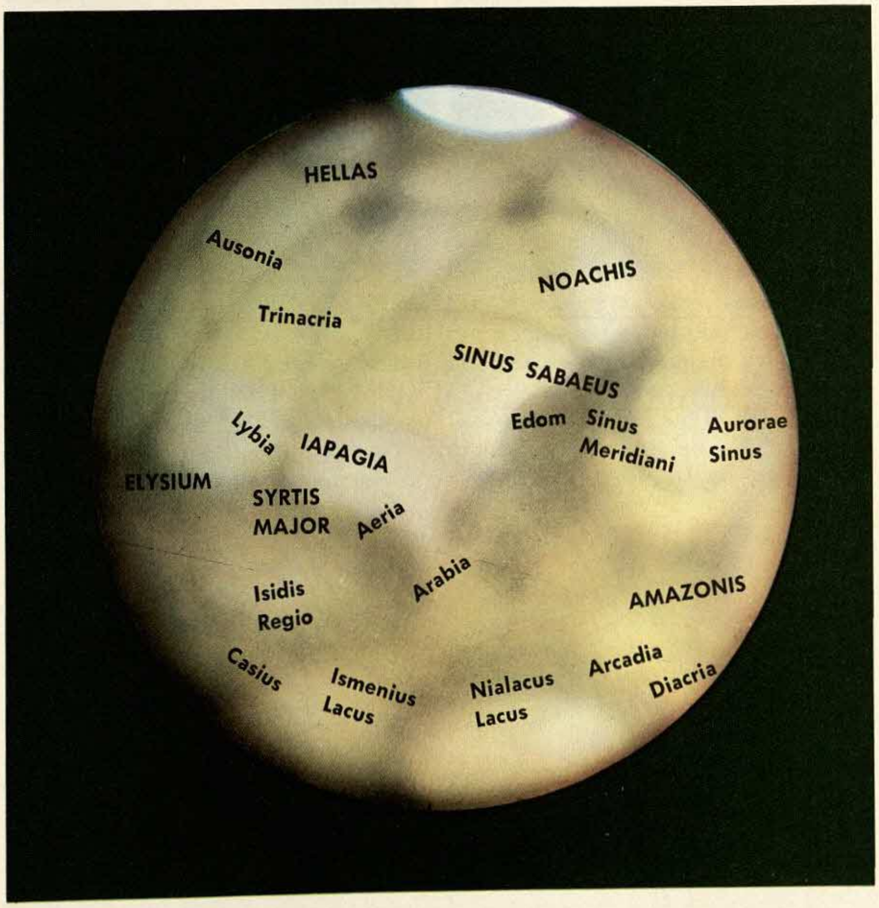
Two highly competent observers who claimed to have observed long thin markings on the face of Mars, colored the same as the Maria (plural of *mare,* Latin for "sea") and running from sea to sea, were the Italian astronomer Giovanni Schiaparelli and the American astronomer Percival Lowell. Because he believed that the maria actually contained water, Schiaparelli called the connecting lines *canali* (Italian for either "channels" or "canals"). Because the lines appeared only during certain seasons, Lowell popularized the concept that the "canals" were built by Martians to permit the circulation of water over the planet.

Other astronomers—including Edward Emerson Barnard, who used the most powerful refracting telescope ever built, the one at Yerkes Observatory—maintained that they had never seen the much-discussed canals on Mars—and their disclaimers had to be taken with the utmost seriousness. Thus began a scientific controversy that lasted for many years but may now be considered to have ended with a refutation of the canal concept because of more recent observations. It is probable that these were markings, so small as to be barely perceptible, among the larger markings that appear during the seasonal cycles. Seen through a telescope with inferior magnifying and resolving power, the markings appeared as filaments. The concept will be finally proved imaginary only when a spacecraft or a moon-based observatory can offer proof—and considering the pace of scientific progress, such proof will soon be available. Space probes in the late 1960s indicated no canals; markings were believed to be attributable to ridges and faults.

THE ATMOSPHERE OF MARS

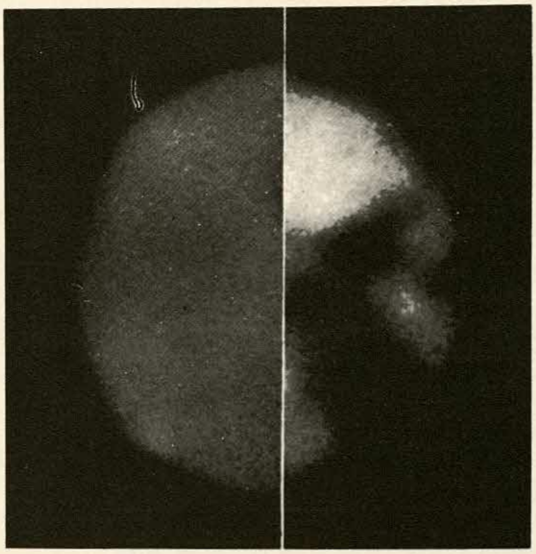
Telescopic observations have already proved that Mars has an atmosphere. One proof is that the surface of the planet is not always equally observable, tending to vary in visibility even during the course of an observation—an effect that can be attributed to an atmosphere that interferes with observation in the same manner as does that of the Earth. Furthermore, the existence of polar caps with variable areas suggests that matter must move over the planet's surface, and the most likely way for this to occur would be

1



THE CANALS — Schiaparelli and other observers designated the large circular features they saw on Mars as seas (maria) and the filaments they perceived connecting some of the seas were termed canals or channels (*canali*). Because the filaments appeared more clearly during the season when the color of the seas intensified, the theory was advanced that the canals were works constructed by supposed inhabitants of the planet. These filaments are now considered random alignments of smaller features or perhaps optical illusions.

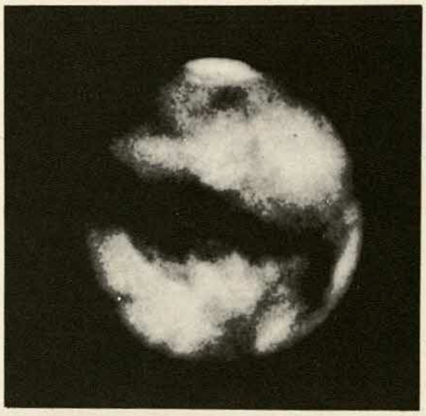
2a



FILTERED PHOTOGRAPHS—In Illustration 2a, two photographs of Mars, one taken through an ultraviolet filter and the other through an infrared filter, were cut in half, and the left half of the first was joined to the right half of the second; the former appears larger. All the other photographs were taken with colored filters: orange (Illustrations 2b and 2d); red (Illustration 2c); and blue (Illustration 2e). The blue filter results in a photograph showing atmospheric haze and makes the planet appear much larger than does the red filter, which, on the other hand, reveals more surface detail.

2d

2b



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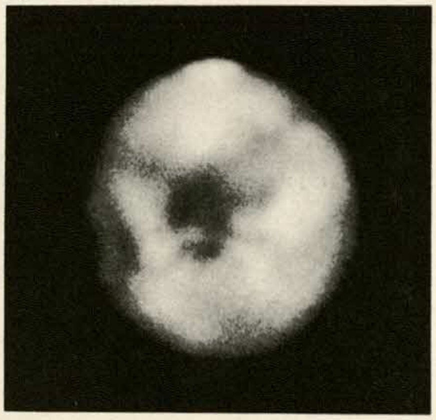

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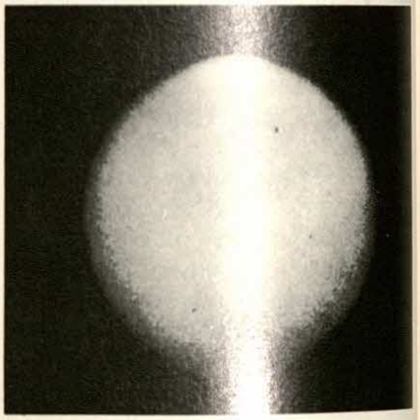


through evaporation and transportation through an atmosphere.

The details of the Martian surface appear blurred at the edges of the observable face, and this accords with the theory of an atmosphere, which would appear thicker at the edge and would, therefore, absorb more light. When the sun's rays illuminate Mars from the side, so that the planet has the appearance of the moon in the ninth or tenth day of its cycle, the part that shines is slightly larger than mathematical calculations would indicate—a phenomenon explicable only by assuming an atmosphere that produces a twilight effect at the edge of the bright side, making it appear larger.

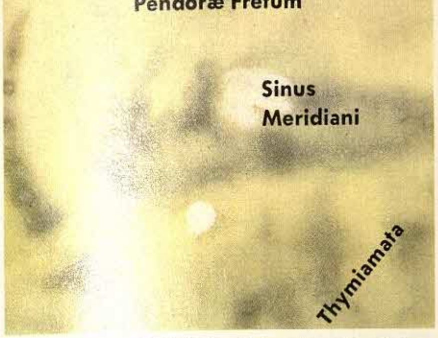
Ultraviolet photographs offer the most convincing evidence that Mars has an atmosphere, for they show mist held in suspension. The composition of the atmosphere is not easily studied; most of the light of Mars—sunlight reflected from the surface—is somewhat colored by the terrain, and only that small fraction of light absorbed by the atmosphere indicates the composition of the atmosphere.

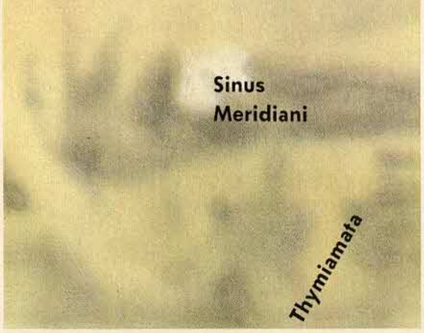
A calculation of the velocity of the molecules in the Martian atmosphere at its present temperature shows that hydrogen and helium can escape, but that nitrogen, argon, oxygen, and other heavier gases are trapped. Spectroscopic analysis, on the other hand, shows that the Martian atmospheric pressure is no more than 5 to 10 percent of the terrestrial atmospheric pressure, and probably ranges between 1 and 2 percent. Estimates of the oxygen and water content have always been low, and according to observations made during the Mariner VII exploration, the atmosphere is almost entirely carbon dioxide, with only traces of oxygen, carbon monoxide, and water vapor.

TEMPERATURE AND CLIMATE

Very delicate instruments capable of measuring the heat radiated at various locations on the surface of Mars indicate the temperature distribution at various regions and times of day, and to some extent reveal climatic conditions. The temperature, as might be expected, is highest at the equator, higher in the summer hemisphere, and higher at noon. At the equator, it may approach 187° C (about 368° F) at noon, fall to 0° C (32° F) at sunset, and, according to one estimate, to about −100° C (−148° F) at night. Such a temperature range is comparable to that on Earth, taking into consideration the greater distance of Mars from the sun and the correspondingly less heat it receives. Moreover, the Martian atmosphere is more rarefied than that of Earth—Mariner analysts found that the atmospheric pressure on the Martian surface was about that found at elevations between about 30,500 and 46,000 m (about 100,000 and 150,000 ft) above the Earth—and so greater correlation is found between the amount of solar heat reaching Mars and the temperature—that is, the Martian surface

3





STATIONARY CLOUDS—Extensive cloud formations frequently cover vast regions of Mars for long periods of time, whereas smaller clouds, such as the banner clouds that are observed over mountains in the Alps, remain over specific features.

would be very hot while the sun shines and very cold when it does not shine.

CLOUDS AND STORMS

It is not yet possible to study the clouds of Mars as those on Earth can be studied, by flying just above them; but when a cloud formation reaches dimensions of 100 km (about 62 mi) or so, its form can be observed; and cloud covers ten times that size are frequently seen covering vast regions for days. Smaller clouds have also been observed remaining near fixed locations on the surface, suggesting the presence of a mountain, with atmospheric humidity condensing near the summit as the winds pass over, much as the banner clouds hover over Alpine peaks on Earth. The larger clouds, on the other hand, move over the planet's surface, indicating winds that may attain a velocity of more than 32 km/hr (about 20 mph).

The features on Mars are sometimes covered or veiled by yellowish mists, which appear mostly in one hemisphere during the spring season and which may be caused by dust blown up from the ground by strong winds. Knowing the thinness of the Martian atmosphere, it can be calculated that these particles must be no larger than 20 μm (about 0.0008 in.) in diameter; it would take about 24 hours for them to descend less than a mile, and they could be kept in suspension by winds of moderate strength.

THE SATELLITES

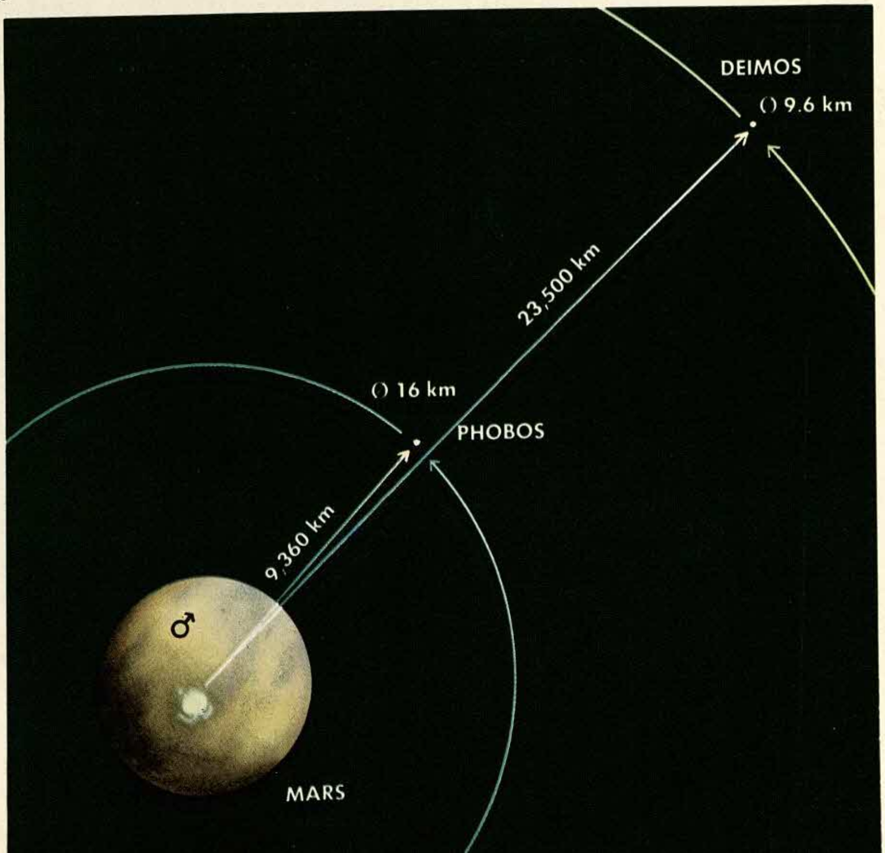
During a major opposition of Mars in 1877, all the telescopes of Europe and America were trained on the planet. At the Naval Observatory in Washington, D.C., the astronomer Asaph Hall utilized the occasion to determine whether the planet had any satellites. After many nights of long and difficult work, he had decided to abandon the project when he spotted a body near Mars that might be the object of his search. He observed it for a time, but poor atmospheric conditions forced him to interrupt his observations; when favorable conditions returned, he found not one satellite but two, moving around Mars with great speed. They have been named Deimos and Phobos, after the two sons of the Greek god Ares (Mars).

Deimos revolves around Mars at a distance of about 23,500 km (about 14,600 mi) miles in a period of 30 hours and 18 minutes. It has a diameter of about 9.6 km (about 6 mi) and would appear from Mars as a disk about 80′ of arc in diameter and as bright as Venus. Phobos is about 9,360 km (about 5,800 mi) from Mars and completes its revolution in 7 hours and 39 minutes. Inasmuch as this is less than a Martian day, Phobos rises in the west and sets in the east twice each day. It has a diameter of about 16 km (about 10 mi) and would appear from Mars as a disk about one third the size of the moon and only one twenty-fifth as bright.

4

STORMS—The features of Mars are sometimes obscured by a yellowish haze, especially during the spring, and the cause of this is believed to be a dust blown up by wind.

5

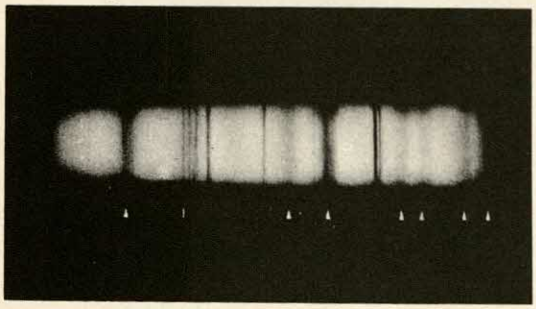


SATELLITES—In 1877 the American astronomer Asaph Hall discovered, during an opposition, two satellites moving with great speed around Mars. The furthest, Deimos, is about 23,500 km (about 14,600 mi) away from the planet, while the nearest, Phobos, is about 9,360 km (about 5,800 mi) away.

JUPITER | the Olympus of the solar system

Since the day when man first turned his eyes and intellect toward the heavens, Jupiter, the giant planet of the solar system, has remained an enigma. Despite its 483-million-mile distance from the sun, Jupiter's brilliance often dominates the evening sky. Its 88,770-mile equatorial diameter dwarfs that of any other planet. Its mass is more than twice that of the eight other planets combined, and its atmosphere is hundreds of miles deep. Yet only in the last century, with the help of increasingly sophisticated instruments and expanding scientific knowledge, have astronomers been able to analyze with any degree of accuracy the physical makeup of this unique planet.

1



JUPITER'S ABSORPTION SPECTRUM—Jupiter reflects a part of the light it receives from the sun. The spectrum of this light contains both the absorption lines of the elements present in the sun and the absorption lines of some elements contained in Jupiter's atmosphere. The spectrum in this photograph reveals the absorption lines of methane (indicated by arrowheads). The line indicated by a dash is ammonia; even though it is less intense than most of the methane lines, it can be deduced that ammonia is at least as common as methane on Jupiter. Because of this chemical composition, the atmosphere of this and similar planets (Saturn, Uranus, Neptune) is described as "reducing."

Basically, the scientific investigation of Jupiter's mysteries has been rooted in studies of the light reflected by Jupiter's dense atmosphere. Through these studies, much knowledge of Jupiter's composition has been gained. The study of the composition of a planet's reflected light is based on photographs taken through appropriate filters, using film sensitive to various wavelengths. When photographed in infrared light, Jupiter's markings appear noticeably similar to those photographed in visible light. (It is not quite accurate to speak of "light" in connection with infrared radiation; however, since infrared radiation makes it possible to obtain photographic images similar to those obtained from visible light, the term is used.) This similarity indicated that even at infrared wavelengths, the atmosphere of Jupiter—with an underlying solid surface—was being observed. By contrast, infrared photographs of Mars give a view of that planet quite different from what one observes optically, leading scientists to conclude that the thin Martian atmosphere is essentially transparent at infrared wavelengths. This consideration, along with theoretical calculations, confirms the idea of a thick Jovian atmosphere.

Astronomers study the composition of Jupiter's atmosphere through spectrographic analysis. Because of Jupiter's extremely low density in comparison with that of the Earth, a substantial difference obviously exists in the composition of the two planets.

SPECTROSCOPIC ANALYSIS OF JUPITER'S ATMOSPHERE

Jupiter's spectrum is studied in the same way as that of other planets: a telescope with a spectrograph attached is directed toward the planet and the spectrum is registered. Then, the moon's spectrum is recorded with the same telescope and spectrograph. In both cases the sun's reflected spectrum is also being observed. In the first spectrographic recording, the solar light reflected by Jupiter's atmosphere has been partially altered by the atmosphere, while in the second the light reflected by the moon's surface has not been altered. After reflection, the light from Jupiter passes through the Earth's atmosphere, undergoing a certain amount of absorption in the process. The characteristics of absorption of solar light by Jupiter's atmosphere appear, therefore, as differences between Jupiter's spectrum and that of the moon. In Jupiter's spectrum, bands corresponding to ammonia and methane have been observed, with ammonia in much greater proportion.

COMPOSITION OF JUPITER'S ATMOSPHERE

Through spectroscopic observation of Jupiter's atmosphere, hydrogen, methane, and ammonia have been directly observed. Ammonia and methane are easily seen in the spectrum as they strongly absorb easily measured wavelengths. The hydrogen molecule absorbs radiation through the relatively weak mechanism of quadruple absorption and is much more difficult to observe. It is detected only because of the abundance of hydrogen in the Jovian atmosphere. Other gases far less abundant than hydrogen will be even more difficult to detect. The mean density of Jupiter's atmosphere can be measured, however, through study of the occultation of stars by the planet; with the resulting data the presence of other elements can be inferred by theoretical calculations.

Studies of the Earth's origin indicate that the Earth and the other planets were probably formed from the same matter that makes up the sun, the stars, and the nebulas. This matter is mostly hydrogen and helium. Yet the Earth and the minor planets have a high density, and hydrogen and helium, so common elsewhere in the universe, seem almost absent. Jupiter, with a mass more than 300 times that of the Earth, has a gravitational field strong enough to retain the lighter elements. It is logical to conclude, then, that Jupiter's extremely low density is due to the presence of hydrogen and helium in great quantities.

CHEMICAL STRUCTURE

Studies of the Earth's interior suggest that the elements are denser in the central part than on the surface because they are highly compressed. Under the pressures present at the center of the Earth even the hardest metals are compressed until their density is considerably increased.

At the center of Jupiter the pressure is much greater than at the center of the

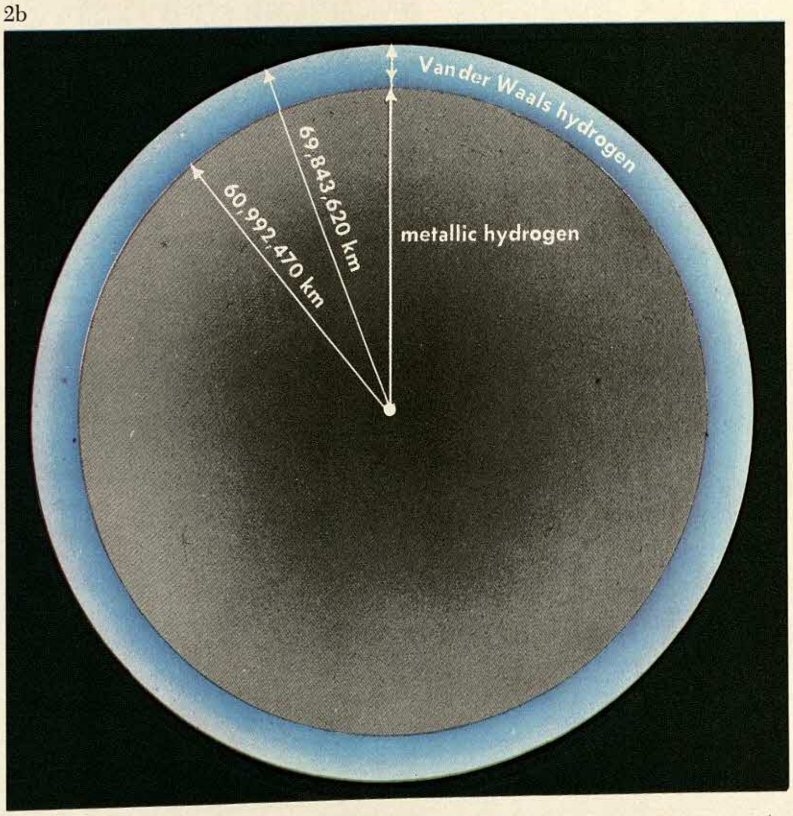
Earth because the thickness of accumulated matter is much greater. Because the force of gravity is much higher on Jupiter than on the Earth, matter inside Jupiter must be very dense. Yet because Jupiter is so light in relation to its size, hydrogen and helium must be its principal constituents. These gases are in fact so light that even compressed inside Jupiter, they give the planet a mean density of 1.3. It is reasoned, therefore, that Jupiter, like a star, is composed mainly of hydrogen and helium. Unlike a star, however, Jupiter is cold, so these gases are condensed and at a certain depth even solid.

The bands and clouds visible in Jupiter's atmosphere are not composed of hydrogen and helium, but of ammonia, which is solid at Jupiter's temperature. Ammonia condenses in the conditions of Jupiter's atmosphere at −120° C (−184° F); at −140° C (−220° F) it is undoubtedly solid. The intense activity of Jupiter's atmosphere could therefore be due to the continuous evaporation and condensation of ammonia. Although the residual heat of the planet is not high enough to raise its temperature appreciably above the value of solar radiation, the heat may be sufficient to cause intense evaporation and "snowfalls" of gas.

The presence of ammonia indicates the existence of nitrogen on Jupiter. Because nitrogen also exists in the sun and other stars, the nitrogen on Jupiter may have formed ammonia when it condensed. A part of the nitrogen could still

2a

2b



JUPITER—A telescopic view of Jupiter (Illustration 2a) reveals the methane and ammonia clouds arranged in bands parallel to Jupiter's equator. The bands cover nearly all the planet's surface. This surface cannot be observed; however, a knowledge of the behavior of solid matter under high pressure enables astronomers to theoretically reconstruct the inside of the planet. The cross section (Illustration 2b) is a model of Jupiter's interior, based on the theory that it is mostly composed of hydrogen, and that it has the same average composition as stellar matter. According to the same theory, Jupiter is composed of Van der Waals solid hydrogen to a depth of about 8,000 km (about 5,000 mi). Below this depth, because of the increase in pressure, metallic hydrogen exists. The metallic hydrogen at the center reaches a density of 3.6.

be in a free state, but such nitrogen cannot be observed spectroscopically.

No satisfactory explanation has yet been given for the coloration observed in the bands and the clouds of Jupiter. It has been noted, however, that sodium and potassium, even in minute quantities, are enough to strongly color ammonia crystals and may be the cause.

ATOMIC STRUCTURE

Among the many uncertainties concerning Jupiter's composition, one fact is certain: the preponderance of hydrogen in its makeup. This fact goes a long way toward simplifying the conjectures that can be made about the planet's internal structure. Understanding of these theories must be based on knowledge of how matter acts under very high pressures. For example, if hydrogen is cooled to the point of solidification, its atoms approach one another in regular positions in space. What holds the atoms in this position? If hydrogen gas is compressed when its molecules or its atoms are far from each other, the gas behaves according to the perfect gas law. Under these conditions hydrogen behaves as if its molecules did not attract one another. Molecular attraction is weak because the molecules are so far apart. However, if the gas is highly compressed so that the molecules are closer together, they are attracted to one another more strongly; the gas behaves as if its molecules were no longer free. At this point, hydrogen does not follow the perfect gas law. Its behavior is described in an equation named after Johannes Van der Waals, the Dutch physicist who first explained it. When the gas solidifies, its atoms are held together by the force with which the molecules had attracted each other when the gas was compressed. Under great pressure, solids are compressed and increase in density, forming a Van der Waals solid. The solid hydrogen which exists near the surface of Jupiter is a Van der Waals solid.

In general, atoms touch one another in an ordinary solid; they become deformed when the solid is compressed. If, however, the pressure is further increased, electrons may detach themselves from the nuclei and become almost free to circulate among the ions that make up the solid. A solid in which all electrons are grouped around their respective atoms is a dielectric; this is the state of Jupiter's surface hydrogen.

If, on the other hand, the electrons are free to move among the atoms, the solid behaves like a metal (and, in particular, becomes conductive). A nonmetallic solid can be compressed and transformed in this way into a metal. At a pressure of about 280,000 kg/cm^2 (about 4 million lbs/in.^{2}), for example, iodine becomes a million times more conductive than under standard atmospheric pressure. At a certain depth below the surface of Jupiter, a pressure is reached sufficient to cause the ionization of hydrogen. From this depth toward the planet's center, the hydrogen is metallic; its density exceeds 3.5 at the planet's center.

EMISSION OF RADIO WAVES

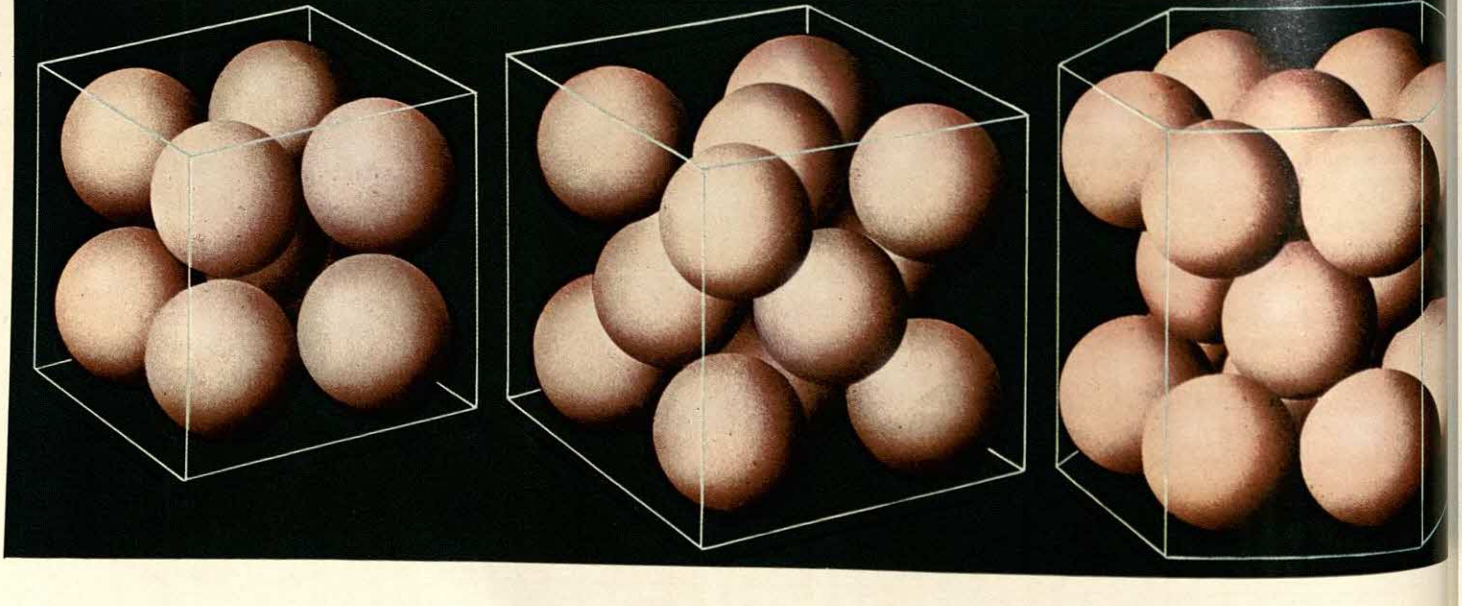
Radio telescopes register very strong emissions of radio waves emanating from Jupiter.

These emissions are divided into two classes according to their wavelength and the emission mechanism. Decimeter radiation is produced by electrons moving at very high speeds in the magnetic fields of Jupiter. This emission—similar to that in a synchrotron accelerator and called synchrotron radiation—is always emitted by Jupiter and contributes to an understanding of Jupiter's magnetic fields. At longer wavelengths Jupiter emits another type of radio emission—decameter emission, which is extremely complex. The complete mechanism of its origin on Jupiter is unknown but it is known to be related to the rotation of the planet and to the position of Io, one of Jupiter's satellites. As observed from Earth, decameter emission varies greatly in strength for reasons connected with Jupiter and because of scintillations imposed by the interplanetary medium. Even though the cause of decameter emission is still unknown it has provided scientists with a valuable tool for the study not only of Jupiter but of the interplanetary medium.

PRESSURE AND DENSITY OF SOLIDS—A solid substance has its atoms arranged in different ways according to the pressure on the substance. The illustration shows three different ways in which atoms can be arranged in a crystal lattice, giving origin to solids which show an increasing density. Illustration 3a is a simple cube lattice, 2b a face-centered lattice, and 2c a compact hexagonal lattice.

3

a b c



JUPITER THROUGH THE TELESCOPE

the giant with the mysterious red spot

Weighing little in relation to its enormous size and distinguished by its strange red spot, Jupiter is the largest of the planets, with a diameter about 11 times that of the Earth. Seen from the Earth, Jupiter is one of the brightest of all celestial bodies. It is outshone only by Venus and occasionally, and for very brief periods, by Mars.

Jupiter's orbit around the sun is about 5 times as large as the Earth's. Unlike Venus and Mercury, which are visible only at twilight because they orbit the sun inside the Earth's orbit, Jupiter is visible all night. When Jupiter rises in the eastern evening sky, it dominates the sky for the rest of the night, dwarfing the stars with its ivory-white light.

JUPITER'S BRIGHTNESS

Jupiter completes its orbit around the sun in a little less than 12 years. It reappears every year in the same position as the year before, but just a little later—either at the same hour one month later, or the same day but two hours later.

Jupiter's mean distance from the sun is 483 million miles. Since its orbit is not a perfect circle, this distance may vary by as much as 46 million miles. The Earth comes within 367 million miles of the giant planet if opposition takes place when Jupiter is at its perihelion (nearest the sun). The Earth is farthest from Jupiter when the giant planet is in conjunction with the sun and at its aphelion (farthest from the sun). Here the distance between the two planets is almost 600 million miles, about one and two-thirds times the minimum distance. Although 600 million miles seems a respectable distance, the difference between the maximum and minimum distances is not enough to have any effect on the brightness of the planet as seen from the Earth. At its maximum distance from the Earth, Jupiter's stellar magnitude is −1.4, almost the same as that of the star Sirius. When Jupiter is in opposition, its stellar magnitude may reach −2.5. In neither case do any stars (as opposed to planets) outshine it.

THE "SQUASHED" PLANET

A telescope or binoculars that magnify 15 or 20 times will reveal Jupiter as a disk rather than a bright spot in the sky. The apparent diameter of this disk is about 50″ (seconds of arc) when a good opposition brings Jupiter close to the Earth, about 40″ when the opposition is not so good, and as little as 32″ when the planet is at its maximum distance from the sun. Under ideal conditions, Jupiter appears about as big as the moon if it is magnified 60 times. Viewed through the largest telescopes, Jupiter appears five to six times as large as the full moon seen with the naked eye. However, even binoculars will reveal that Jupiter's disk is actually elliptical, rather than perfectly circular, and that its longer axis lies along the planet's equatorial zone.

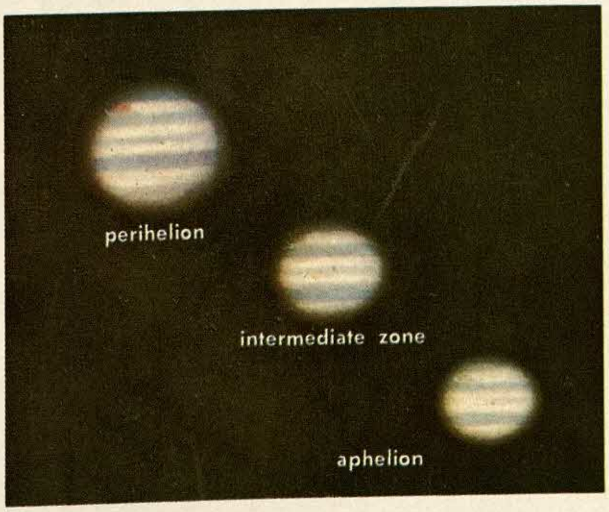
The flatness at the two poles is due to the planet's high rotational speed and to its large diameter; these two factors combine to produce enormous centrifugal force, which causes the planet's equatorial zone to bulge. The pole-to-pole diameter is about 1/15 less than the diameter at the equator.

HUGE BUT LIGHT

When a planet is surrounded by a host of satellites, as is Jupiter, its mass can be easily calculated. With Jupiter the calculation is easier still, because its mass is great enough to cause obvious disturbances in the movement of Jupiter's moons as they pass close to the planet. The mass is calculated by working out the gravitational effect Jupiter has on its moons. On this basis, it has been calculated that Jupiter's mass is exactly 1/1047.40 of the sun's mass, or 318.35 times that of the Earth.

By dividing the planet's mass by its volume, Jupiter's density can be determined. This turns out to be only 1.35 times the density of water. This is slightly

JUPITER AS SEEN FROM NEAR AND FAR— Jupiter's apparent size varies according to whether it is observed at its perihelion or its aphelion: it appears much larger at its perihelion (top left) than at its aphelion (bottom right). At an intermediate point, its size seems halfway between the two. But whatever its position, no star in the sky outshines it.

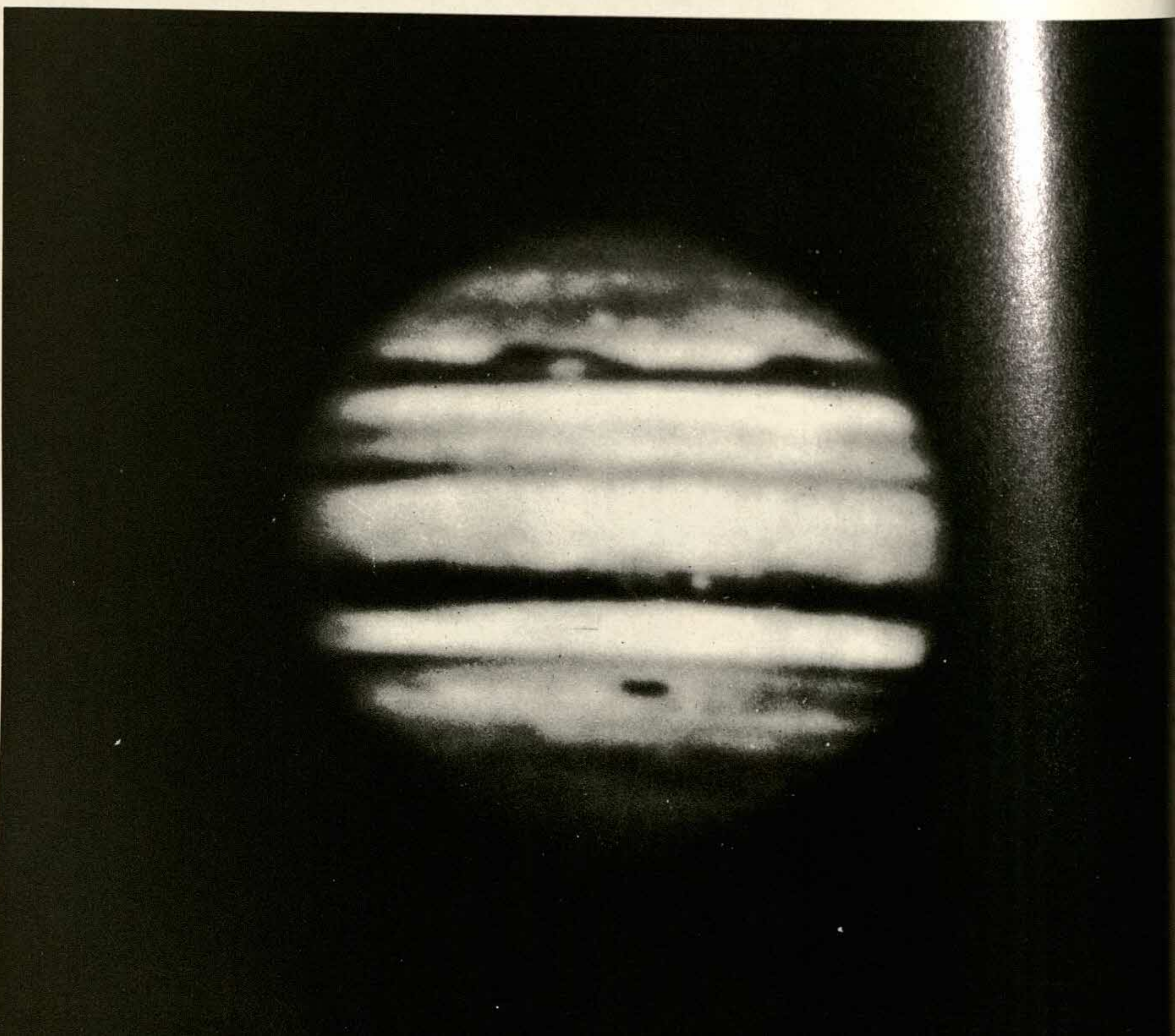


lower than the sun's density, which is 1.41 times that of water.

ROTATIONAL SPEED

The marked flattening at each of Jupiter's poles is not the only distinctive feature of the giant planet; its rotational speed is also remarkable. Jupiter is the fastest-rotating planet in the solar system, making a complete turn on its axis in about 9 hours and 55 minutes. This speed varies according to latitude. For example, the period of rotation at the equator is about 9 hrs 50 min, but once outside the equatorial belt the period of rotation increases by about 5 min. Although this may bring to mind the differential rota-

THE CHANGING PLANET—The rapidly changing face of Jupiter is due to the variable nature of its clouds and its high rotational speed. It takes as little as two hours for any given feature on the surface to change position.



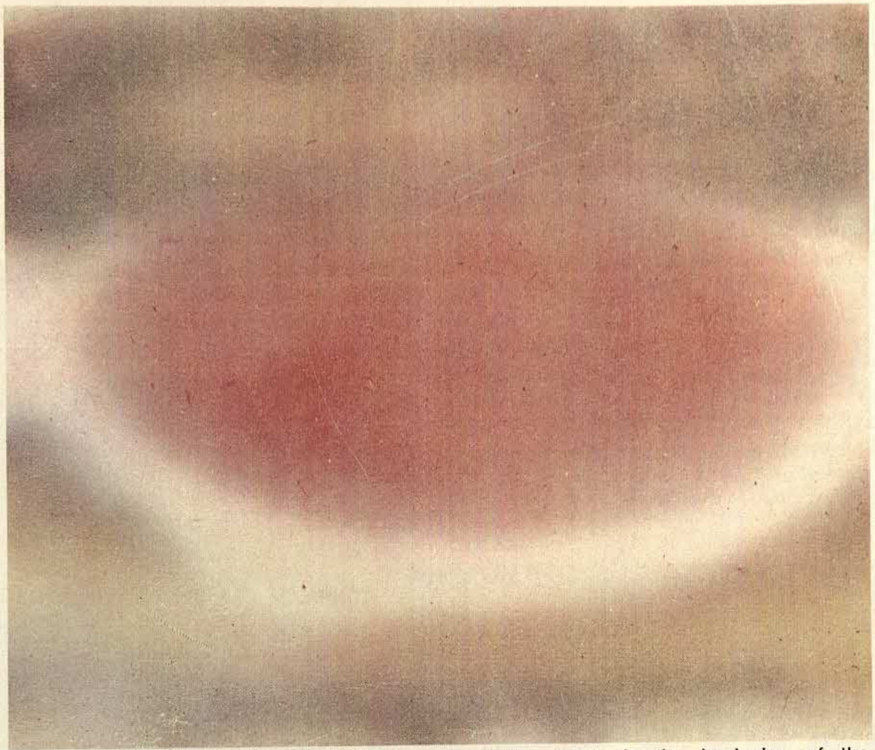
tion of the sun, the two phenomena differ. The sun's rotational speed increases regularly from the equator to the poles, whereas Jupiter's rotational speed varies irregularly. In any given latitude belt the speed is everywhere the same, but the rotational speed of the two hemispheres differs. Some of the spots on Jupiter's surface move at a speed of nearly 200 mi/sec. These spots appears and disappear in the space of a few days or a few months.

JUPITER THROUGH A TELESCOPE

Jupiter is one of the most rewarding of the planets from the stargazer's viewpoint; there is always something interesting to see. There is no need to wait until the planet is in a good phase or is close to the Earth, since there are few times in the year when Jupiter is invisible or difficult to observe.

Powerful binoculars or a small telescope reveal the belt-shaped patches crossing the planet parallel to its equator, and a pair of wide bands completely encircling the planet are usually visible. Through a larger telescope, other belts are sometimes visible at higher latitudes; these belts often vary in breadth from place to place. Viewed through a really powerful telescope under good atmospheric conditions, the larger belts appear to have jagged edges, and small spots appear from time to time on the rest of the planet's surface. The colors of these spots —beige, olive-green, and reddish-brown —stand out against a brown-tinted, ivory-colored background. Through the same powerful telescope, Jupiter's rotation can be observed, since any given spot or patch will cross 70 percent of the planet's disk in about 2½ hrs.

If an observer makes drawings of the position of Jupiter's belts every evening and compares the drawings, he will see how the belts vary in intensity and how their latitudinal positions change. Jupiter's differential rotation can be observed by noticing how the details of two adjacent belts draw away from each other on successive rotations.



THE MYSTERY OF THE RED SPOT—Studied systematically since 1878, Jupiter's red spot has long intrigued astronomers. So far no one has been able to explain its origin or its distinctive color. At the beginning of the present century the spot went through a period when it lost much of its color, which it has subsequently regained.

SEMIPERMANENT FEATURES: THE RED SPOT

Although the belts near the equator shift latitudinally a little and vary somewhat in intensity, they remain close to the planet's equator. These belts give the planet its special character, and they are classified as a semipermanent feature of Jupiter's surface. The most striking feature of the planet's surface, however, is the famous "red spot."

Although the spot had been observed some time before 1878, it was in that year that astronomers began a constant and systematic study of the spot. The spot covers an elliptical area about 30,000 mi long and about 7,000 or 8,000 mi wide and varies in color from an intense brick-red to a faint gray. At times it has lost all its color and become invisible.

Theories of all kinds have been put forward as to how the spot may have originated. One theory claimed that the phenomenon was due to "eruptions" on the surface of the planet; but if this were true the spot would be stationary on Jupiter's surface. The "eruptions" theory is contradicted by the fact that the spot, since the time systematic study began, has rotated erratically as much as 1,080° in longitude with respect to the clouds near it.

A COLD PLANET

Jupiter's temperature can be measured with some degree of accuracy, although the measuring process is not without its problems. These problems arise not from the planet's great distance from the Earth, but from the fact that astronomers do not know exactly which one of Jupiter's atmospheric layers they are measuring.

The layer that is visible to the eye is known to have a temperature of about −140° C (−220° F). This temperature remains the same, due to the heat-giving radiation that Jupiter receives from the sun. Jupiter's temperature is apparently due solely to solar radiation, since the planet appears to lack any appreciable quantity of its own heat.

JUPITER'S SATELLITES | the planet with the most "followers"

Jupiter, the largest of the planets in the solar system, also has the most satellites. At least 12 satellites are known to revolve around Jupiter—a planet that almost resembles a complete solar system in miniature.

Of the 12 satellites, four are large enough to rival in size the smallest planets of the solar system, Mercury and Mars. These four were discovered by Galileo. Observing Jupiter through his telescope, he quickly realized that certain celestial bodies surrounding it were not just small stars in the background, but bodies that followed the planet in its movement across the heavens. These four bodies, Galileo noted, seemed to move around Jupiter, which, therefore, seemed to resemble a model of the Copernican concept of the solar system.

In honor of the Medici family, wh were his patrons, Galileo gave the fou moons the collective name of Medicea Bodies. Later, names drawn from my thology were assigned to the satellites Io, Europa, Ganymede and Callisto, i order of their increasing distance fro the planet.

The next of Jupiter's satellites—V—wa discovered by the American astronome

JUPITER'S SATELLITE SYSTEM—The numbers indicate the order in which the satellites were discovered. At the top left is the relationship between the circumference of Jupiter (♃) and its satellites. The four largest—those whose orbits are in white—were discovered by Galileo; they would be visible to the naked eye they were not so close to Jupiter's dazzlin light.

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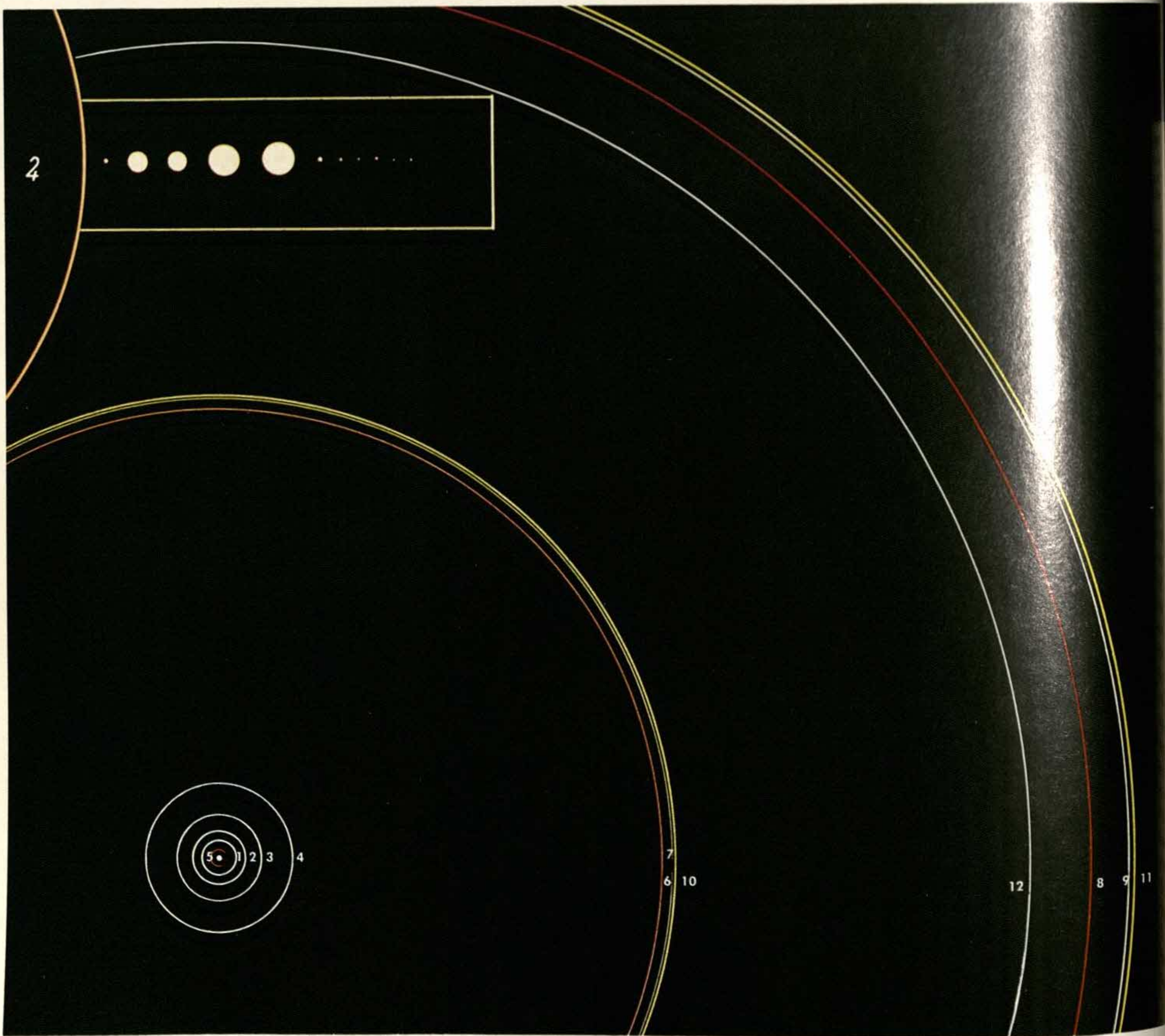

Number	Name	Discoverer and year of discovery	Average distance from the planet, km	Sidereal period days	Diameter, km
V	Amaltea	Barnard 1892	180,000	0.4982	240
I	Io	Galileo 1610	422,000	1.7691	3,230
II	Europa	Galileo 1610	671,000	3.5512	2,880
III	Ganymede	Galileo 1610	1,100,000	7.1546	5,020
IV	Callisto	Galileo 1610	1,880,000	16.689	4,460
VI		Perrine 1904	11,460,000	250.62	160
X		Nicholson 1938	11,580,000	254.21	24
VII		Perrine 1905	11,750,000	260.07	56
XII		Nicholson 1951	20,920,000	631	23
XI		Nicholson 1938	22,530,000	692.5	31
VIII		Melotte 1908	23,490,000	738.9	56
IX		Nicholson 1914	23,660,000	758	27

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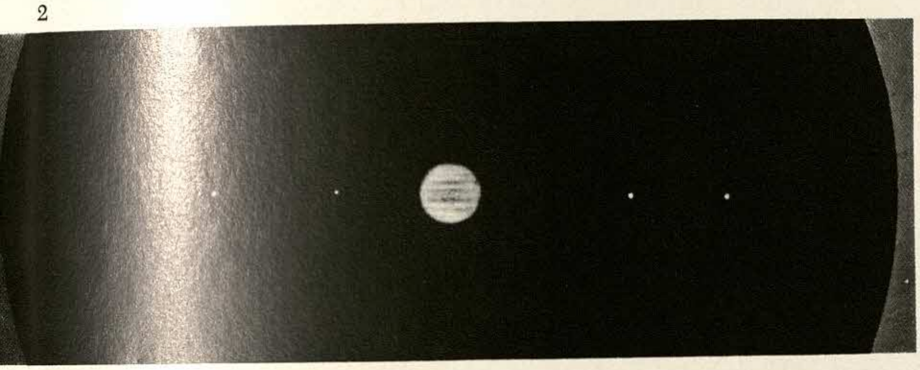

THE SATELLITES OF JUPITER—The satellites are listed in order of their increasing distance from Jupiter. Satellites VIII, IX, XI, and XII revolve in a retrograde direction.

Edward Barnard in 1892. It is a celestial body of the 13th magnitude, with very weak light dimmed by the powerful light of the planet, to which it is quite near. As instruments for celestial observation were perfected, the remaining seven known satellites were discovered.

JUPITER'S SATELLITE SYSTEM

Only the first five of Jupiter's satellites to be discovered have been given names; the others are indicated by Roman numerals in the order of their discovery. The four largest are so luminous (Ganymede, for example, is a body of the 5th magnitude) that they would be visible to the naked eye if they were not so close to Jupiter's bright light. The other satellites are so weakly luminous that they cannot be identified without time-exposure photography. Satellite V, closest to Jupiter, revolves around the planet at a distance almost equal to the diameter of the planet itself. The most distant satellites are so far off that they appear to be separated from the planet's disk by a distance equal to three times the apparent diameter of the Earth's moon.

The satellites closest to Jupiter revolve around it in 12 hours. The most distant take about two years—about 1,500 times longer. By comparison, Mercury, the planet closest to the sun, revolves around the sun in a period that is about 1,000 times shorter than the time taken by Pluto, the most distant of the planets. In this sense, Jupiter's satellite system shows greater variety than the solar system.

The comparison of dimensions is no less surprising. While the smallest of Jupiter's moons have diameters of only some tens of kilometers and can be considered to be modest sized asteroids, the largest reach and surpass planetary dimensions. Two satellites are about the same size as Mercury and only slightly smaller than Mars: Ganymede and Callisto have diameters of 5,020 km and 4,460 km (about 3,120 and 2,770 mi), respectively, while the diameter of Mercury is about 4,800 km (about 3,000 mi).

OBSERVING THE SATELLITES

The larger satellites appear as small disks when observed through telescopes with

PORTA MOLINO—From this tower in Padua, Italy, Galileo discovered the first four satellites of Jupiter. In honor of his patrons, he named the collective bodies Medicean.

3

strong magnification. During the past century, many attempts were made to identify some permanent marks on the surfaces of these larger satellites, and only in the last few decades have attempts been made to draw maps of their surfaces. The difficulties encountered were enormous.

Under the best viewing conditions, these satellites appear in the telescope about a twentieth the size of Mars; seen through an instrument with a magnification of 1,000, they appear about as Mars does through an amateur's telescope. Nevertheless, permanent spots have been discovered indicating that the actual surfaces of the satellites—rather than just their atmospheres—are being observed.

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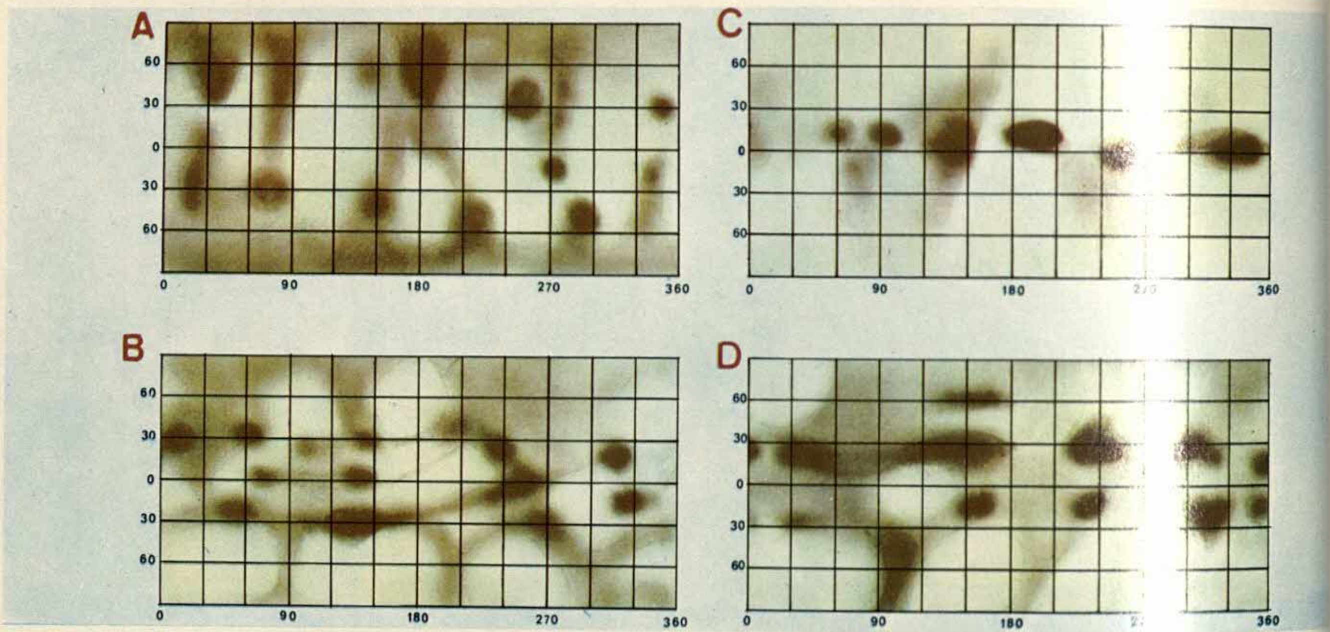

MAPS OF THE SURFACES OF THE SATELLITES—These maps all show similar characteristics, particularly in that the spots are all placed in a certain alignment at the same latitude. Io and Callisto (**A** and **D**) have two rows of spots. On Io, the bands with the spots are midway between the poles and the equator; on Callisto, they are closer to the equator. Europa (**C**) has only one row of spots, located on the equator. Ganymede (**B**) has three rows placed irregularly.

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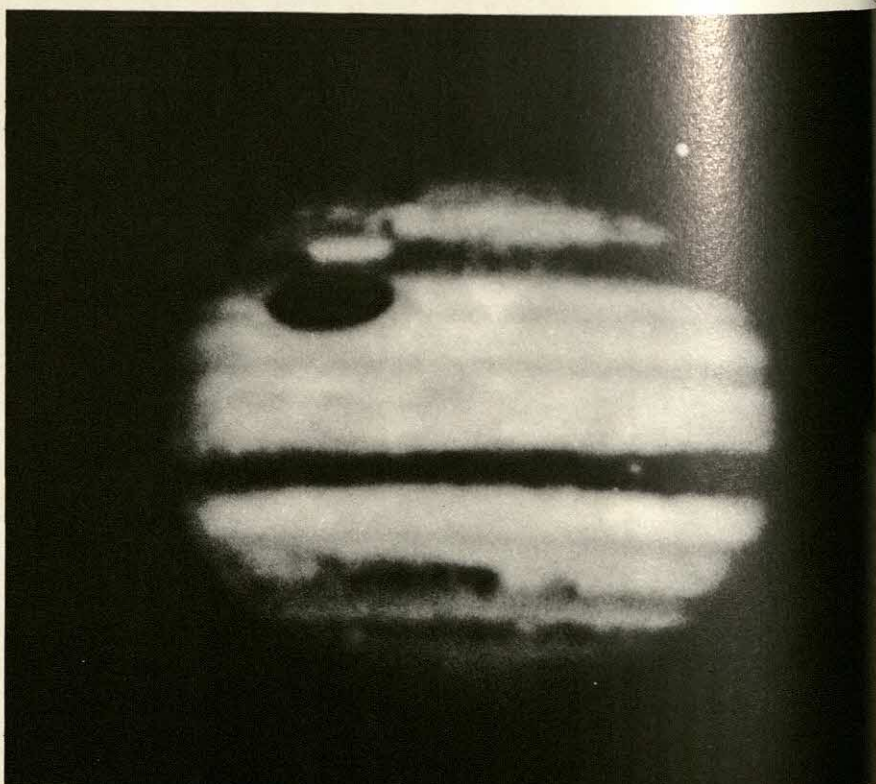
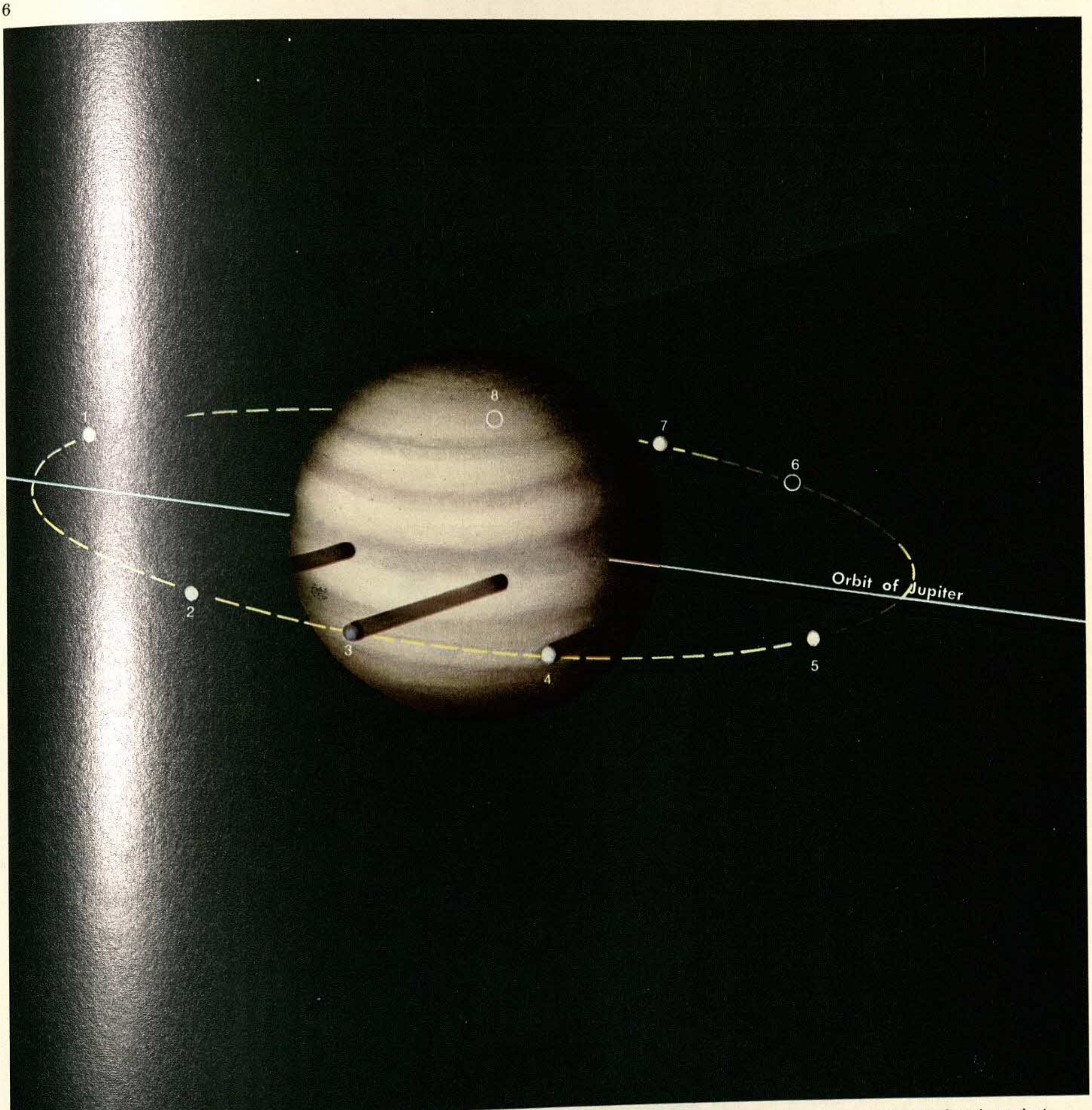


SOLAR ECLIPSE ON JUPITER—This photograph, taken by the 200-in. Mount Palomar telescope, shows the satellite Ganymede slightly higher and to the right of Jupiter as it projects its shadow on the planet. The shadow appears as a black disk somewhat larger in size than the satellite itself. The strong magnification makes the satellite visible as a small disk rather than simply a luminous point.



ECLIPSES, TRANSITS, AND OCCULTATIONS—Jupiter's four principal satellites provide an interesting celestial spectacle—one that can be enjoyed by anyone with a telescope, even a small one. The show varies from evening to evening, as the satellites appear first on one side of the planet, then on the other. Sometimes they are so close to one another that they seem to merge together; at other times they are far apart. Published tables are available, indicating the day-to-day positions of the satellites with respect to the planet and indicating, in advance, the interesting observations that can be made.

The four large satellites revolve in orbits so close to the plane of Jupiter's orbit, and so near to the planet itself, that they project their shadows on the planet whenever they pass in front of it. Moreover, every time that the Earth, Jupiter, and one of the satellites between the two planets are aligned, the satellite's image is projected on Jupiter. If, on the other hand, the satellite is behind Jupiter, it is occulted.

The illustration shows the possible relationships between the satellites and the planet:

1. Eastern elongation (to the left for a terrestrial observer).
2. Solar eclipse: the satellite projects its shadow on the planet, but from Earth is seen to the left of Jupiter.
3. Eclipse and transit: from Earth, the satellite is seen projected on the planetary disk; its shadow falls on the planet.
4. Transit: the satellite passes in front of the planet, but its shadow does not fall on it; the best condition for showing up details of the satellite's surface is against the luminous background of Jupiter rather than the black background of the sky, against which the satellite is too brilliant.
5. Western elongation (to the right for a terrestrial observer).
6. Lunar eclipse: the satellite is hidden by the shadow of the planet; when it reemerges it will be in position 8, where it will be occulted.
7. Satellite elongated (displaced) to the right of Jupiter between an eclipse (position 3) and an occultation.
8. Occultation: the satellite, even though illuminated by the light of the sun, is not visible, because it is completely hidden behind the planet.

SATURN | its composition and structure

As one of the five planets visible to the naked eye, Saturn—like Jupiter, Venus, Mars, and Mercury—has been known and studied since ancient times. Until 1781, the year Uranus was discovered, Saturn was believed to mark the outer limit of the planetary system.

Much less luminous than Jupiter, Saturn slowly follows its long path along the ecliptic, completing a revolution around the sun once every 29½ years. Its average distance from the sun is about 886 million miles, almost double that of Jupiter.

DIMENSIONS OF SATURN

Saturn's apparent diameter varies from 14″ to 20″ (seconds of arc), according to the planet's distance from the viewer. Although Saturn is almost as large as Jupiter, from the great distance at which it is observed it never appears as large as Mars. Saturn is an easy subject for observation with a telescope, however, because its rings have a much greater diameter than the body of the planet.

The rings surround the planet at its equator, thus masking Saturn's strongly elliptical shape. The disk of Saturn is much more flattened at the poles than is Jupiter, and is the most flattened of all members of the planetary system. The polar diameter is about 108,000 km (about 67,000 mi), while the diameter at the equator is about 121,000 km (about 75,000 mi)—a difference amounting to well over 10 percent of the planet's average diameter. However, when viewing the planet's disk through a telescope, it is not easy to see this flattening, because Saturn's rings are situated parallel to the larger diameter, producing an optical illusion that makes it appear less elongated than it actually is.

THE LIGHTEST PLANET

Saturn is about 9 times larger in diameter than the Earth, and approximately 744

MAXIMUM APERTURE—This color photograph (Illustration 1) of the planet Saturn was taken with a telescope of 1.5 m (about 60 in.) diameter. The difference in brightness of the various parts of the rings is clearly evident.

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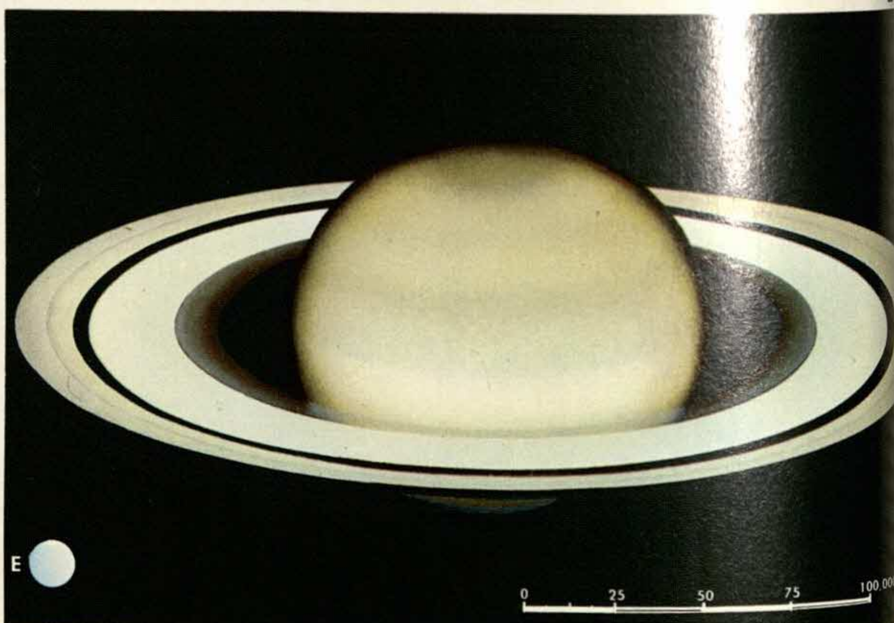

ALMOST A BRIDGE BETWEEN THE EARTH AND THE MOON—The diameter of Saturn's outermost rings is 275,000 km (about 171,000 mi), and is about two-thirds the distance between the Earth and the moon. Visible (from inside to out) are the "crepe" ring, the variations in brightness of the principal ring, Cassini's division, and the outside ring with Encke's division (Illustration 2).

times greater in volume. However, the planet's mass, which can be calculated easily by observing the period of rotation of the satellites, is equal to only about 95 times that of the Earth. Saturn's density is 0.715. With this low density, the planet would float if it were placed in water.

Because of its low density, Saturn's gravitational pull is only slightly more than that of the Earth. On Saturn, however, the value of gravitational acceleration is 30 percent greater at the poles than at the equator, owing to the extreme polar flattening. On the Earth, the variation of gravitational acceleration between the poles and the equator is only 5.3 percent.

SPEED OF ROTATION

The rotation of Saturn is difficult to observe. Through the telescope the planet's surface seems to have a very uniform aspect. The few visible details are patches in the form of bands resembling those on Jupiter, but with less contrast and no indentations along the edges. These bands do not enable an observer to chart the planet's rotation. Sometimes patches lasting a short time appear between the bands. When these patches survive more than one rotation of the planet, they change shape and size. Only very rarely does a patch appear that is large and stable enough to allow a fairly accurate measurement of rotation. Even under such conditions, the measurement is uncertain because not all large, stable patches yield the same figure for the velocity of rotation. Because of this, the discovery of new patches is always important to the continuing study of Saturn's rotation. Thus, observations by amateur astronomers provide an important contribution to the research of Saturn's rotation, for such observations can provide information about new patches in time to allow measurements.

Judging by the periods of rotation of the patches, Saturn, like Jupiter and the sun, seems to rotate at different speeds in different latitudes. Near the planet's equator, a period of rotation of about 10 hr and 14 min has been estimated. Near the poles the rotation period is greater. At a latitude of 36°, it has been estimated at 10 hr 38 min.

The period of rotation can also be estimated by means of spectroscopic analysis of the Doppler effect, the same method used to measure the rotation of the sun and the recessional speed of galaxies. Using this method, the speed of Saturn's rotation at latitude 57°, for example, is more than one hour slower than at the equator.

Determination of Saturn's rotational variations is made possible by observation of the planet's dense atmosphere, with its stable currents of different speeds at different latitudes. These are exceptional currents, moving at the equator at a speed of nearly 1,500 km/hr (about 930 mph) in the direction of the planet's rotation.

Saturn's axis of rotation is inclined 26° 45′ with respect to the plane of the orbit (slightly more than that of the Earth). Accordingly, Saturn exhibits a seasonal phenomenon corresponding to that of the Earth. However, different latitudinal zones of the planet receive different quantities of light and heat, with the result that the atmosphere is heated to a greater or lesser degree. Existing instrumentation cannot determine what climatic variations take place on Saturn's surface, because the surface is covered by such a thick atmosphere.

SATURN THROUGH THE TELESCOPE

As noted earlier, Saturn does not show well-defined patches as does Jupiter. The surface features that can be seen—particularly the large bands parallel to the equator—have a longer duration than do those of Jupiter. The position in which

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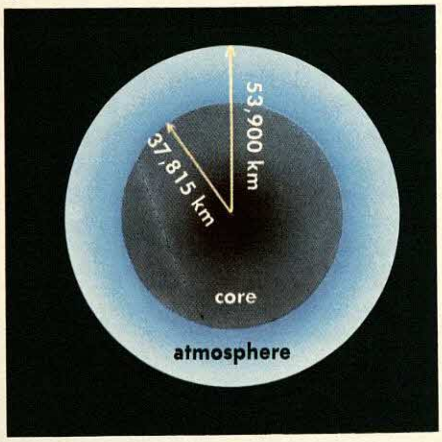


THE INTERIOR OF SATURN

these bands appear is remarkably constant.

Broadly speaking, Saturn's polar zones are darker than the rest of the planet, with a coloration very close to blue-green; the equator appears furrowed by a yellowish band, while other bands are localized in the intermediate zones.

To the eye, Saturn's brightness is affected not only by its varying distance from the sun, but by the position of its rings. When the rings are seen edgewise, they are scarcely visible, sending only a negligible amount of light to the Earth. At such times, even in opposition, Saturn appears of first magnitude. If, on the other hand, the planet is in opposition with the rings seen obliquely, Saturn shines brighter than any of the stars with the exception of Sirius and Canopus.

CHEMICAL COMPOSITION

The spectroscope is used to study Saturn's chemical composition. The difficulties encountered are the same as for Jupiter; the lines and bands characteristic of only the more predominant molecules in the atmospheres of both planets appear in the spectrum.

Saturn has a composition quite similar to that of Jupiter. Analysis of the planet's

atmosphere shows that it contains more methane than ammonia. The reflecting power of Saturn's surface is 0.42, less than that of Jupiter and Venus, but much higher than Mercury's or the moon's. These comparisons are important; they show that Saturn has a reflecting power comparable to all planets having an atmosphere, and much more than those that do not. As an example of the reflective quality of atmosphere, astronauts in space see the Earth as brighter when it is covered with clouds than when the atmosphere is clear.

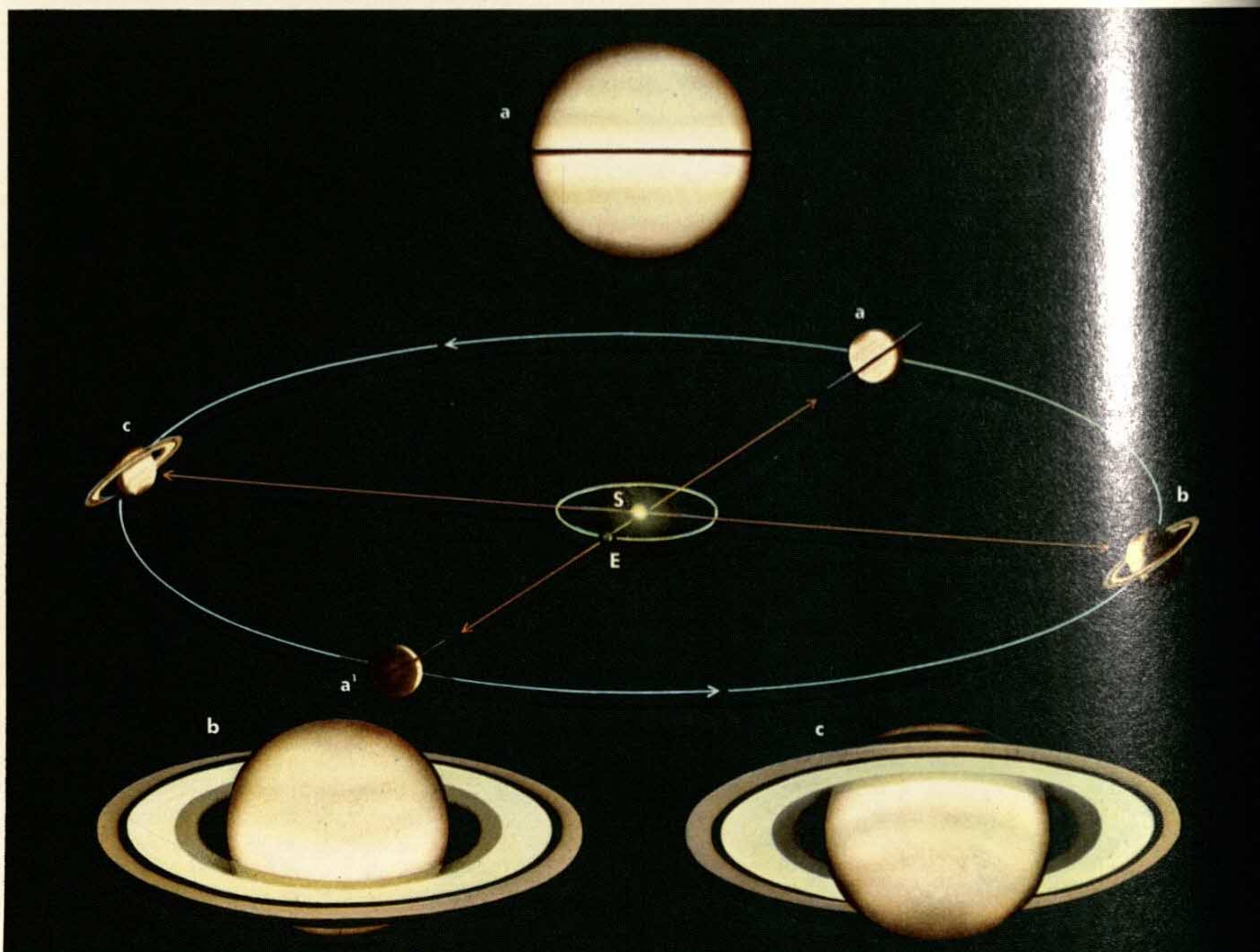
PHYSICAL MAKEUP

The surface temperature of Saturn is estimated at about −150° C (−238° F), making it an icy, forbidding world in which ammonia is solidified. However, the fact that traces of ammonia have been detected, through spectroscopic measurement, in Saturn's atmosphere indicates that somewhat higher temperatures prevail above the planet's surface. This is not the result of heat from inside the planet but is caused by the retention of some heat from the sun in the upper layer of Saturn's thick atmosphere.

The internal structure (Illustration 3) of Saturn is very similar to that of Jupiter. Because of a lower mass and gravitational pull at the center of the planet, however, the hydrogen that is its main element is less compressed, so that its density appears less than that of Jupiter.

The fact that Saturn has a thick atmosphere that is included in its volume (Illustration 3) does not give rise to a wrong estimate of its density, for its atmosphere is relatively thin in comparison with the planet's total radius.

THE FACES OF SATURN—In its orbit around the sun, Saturn's axis of rotation is always fixed in space. An observer on the Earth, which has a very small orbit in comparison to Saturn's, always sees the planet practically from the center of its orbit. Thus, according to the position of Saturn, the rings are visible to a greater or lesser degree. In positions **a** and **a'**, when the rings are seen edgewise, they are almost invisible because they are so thin. In **b** and **c**, however, the rings are seen to the maximum extent and are visible, respectively, from the north and from the south. These are the best positions for observations.



SATURN'S RINGS | planetary ice and gravel

In 1610, Galileo fixed his telescope on Saturn and discovered that the planet had an extremely strange appearance. His primitive instrument showed him only a confused image of a spherical planet with what seemed to be a celestial body on either side. This sighting was the cause of much perplexity; if Saturn, like Jupiter, was accompanied by two moons, why were they so large, comparable in size to the planet itself? And why did they not rotate around it? Galileo's perplexity increased when, making an observation of Saturn several years later, he saw the planet without its two "moons."

Galileo's questions were answered some years later. In 1655, the Dutch astronomer Christiaan Huygens, observing Saturn through a much more powerful instrument than Galileo had used,

THE DANGER ZONE—None of Saturn's satellites orbits closer to the planet than the external diameter of the ring system. On the other hand, the material that forms the rings is closely confined within the limits of the largest of the rings. Between the external diameter of the rings and the orbit of the closest satellite is a zone where any intruding planet or satellite would be destroyed by tidal action.

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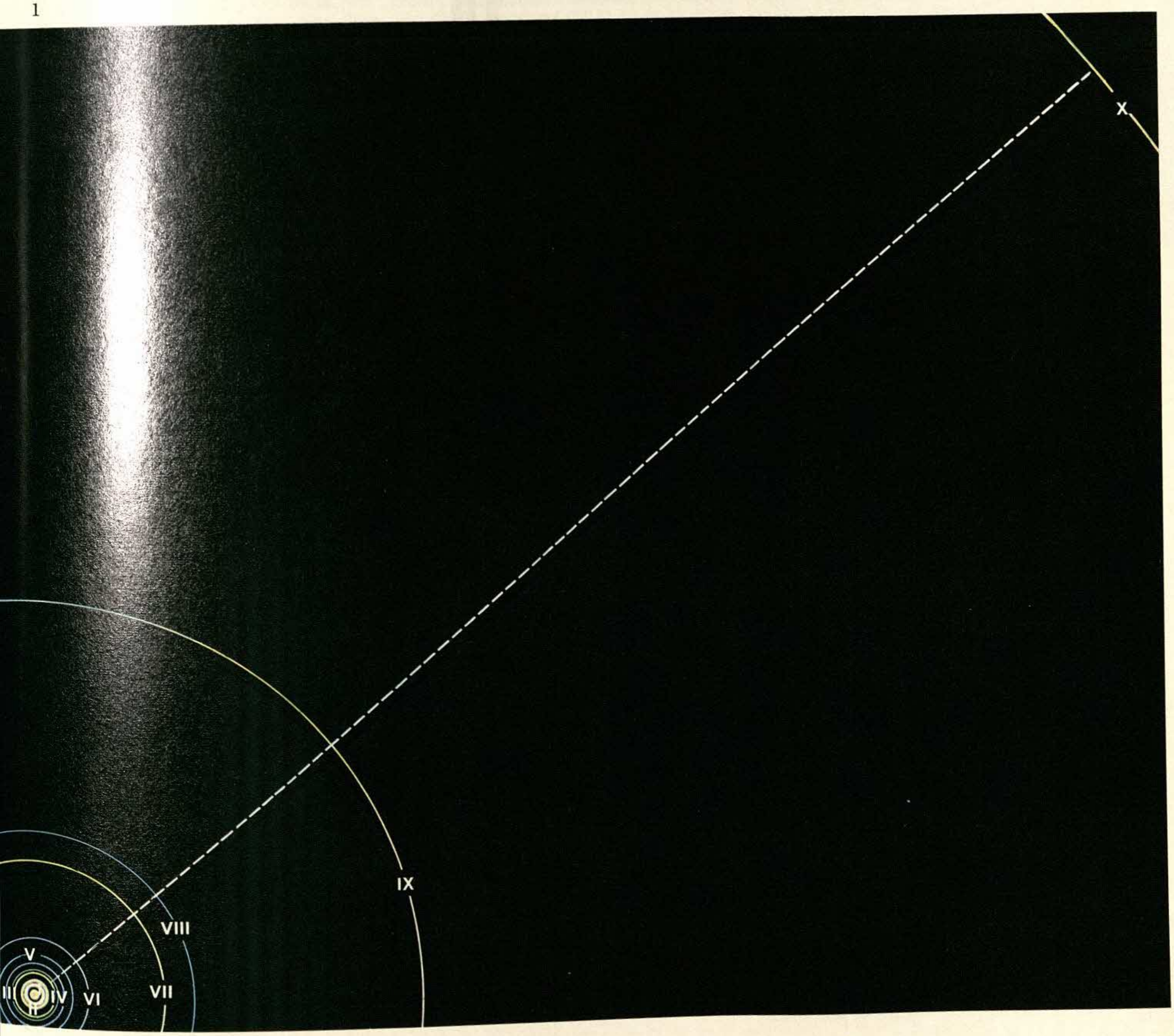

RINGS OF DUST PARTICLES—This imaginative representation shows Saturn's rings, which are probably made up of ice and gravel fragments orbiting the planet.

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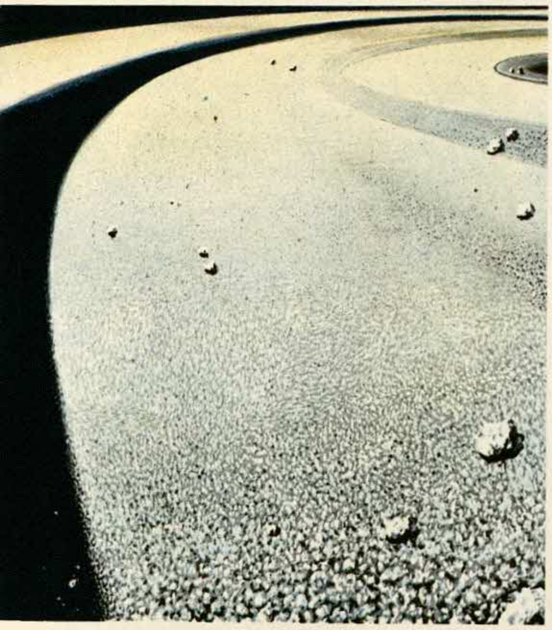

THE RINGS—Some of the more interesting characteristics of Saturn's rings can be seen through a powerful telescope. Their external diameter is well over 275,000 km (about 170,000 mi), exceeding the equatorial diameter of the planet by nearly 153,000 km (about 95,000 mi). A powerful telescope will also reveal the chief division of the ring, which takes its name—Cassini's division—from its discoverer. It divides the ring into two concentric rings, the inner of which is much brighter than the outer. The outer ring, called ring A, is about 16,000 km (about 10,000 mi) wide. The breadth of Cassini's division is estimated at about 2,800 km (about 1,750 mi) and the brighter ring, ring B, is about 26,500 km (about 16,500 mi) wide. The brightness of ring B decreases from the outer to the inner edge where it is separated from a third ring by a gap of about 1,000 km (some 620 mi). This third ring, the innermost of all, is called the "crepe ring," or ring C. This transparent ring, about 16,000 km (some 10,000 mi) wide, is very difficult to detect. Between its inner edge, which is not clearly defined, and the surface of the planet is still another gap of about 11,000 km (about 6,800 mi). The body of the planet itself can be seen through the veil of this inner ring.

Under favorable conditions, observers can see the shadow cast on Saturn's surface by the rings. Accurate measurements prove that the plane of the rings coincides exactly with the equatorial plane of the planet. Since this plane is inclined to the plane of Saturn's solar orbit, it is possible to see the rings either obliquely or side-on. Viewed obliquely, they appear extremely wide and bright, and their light, added to the already bright reflection of the planet, presents a marvelously luminous image. Side-on, the rings are completely unobservable, proving that the thickness of even the brightest of the rings is less than 16 km (some 10 mi). A thicker ring could be seen and photographed. With an extremely powerful telescope, an observer can see that ring A is divided into two parts. Sometimes the gap appears to be an actual split between the two sections while at other times it seems more like a defining line without actual separation. This division is called Encke's division, after its discoverer. Ring B also seems to be marked by a number of divisions that can be seen only with a powerful telescope.

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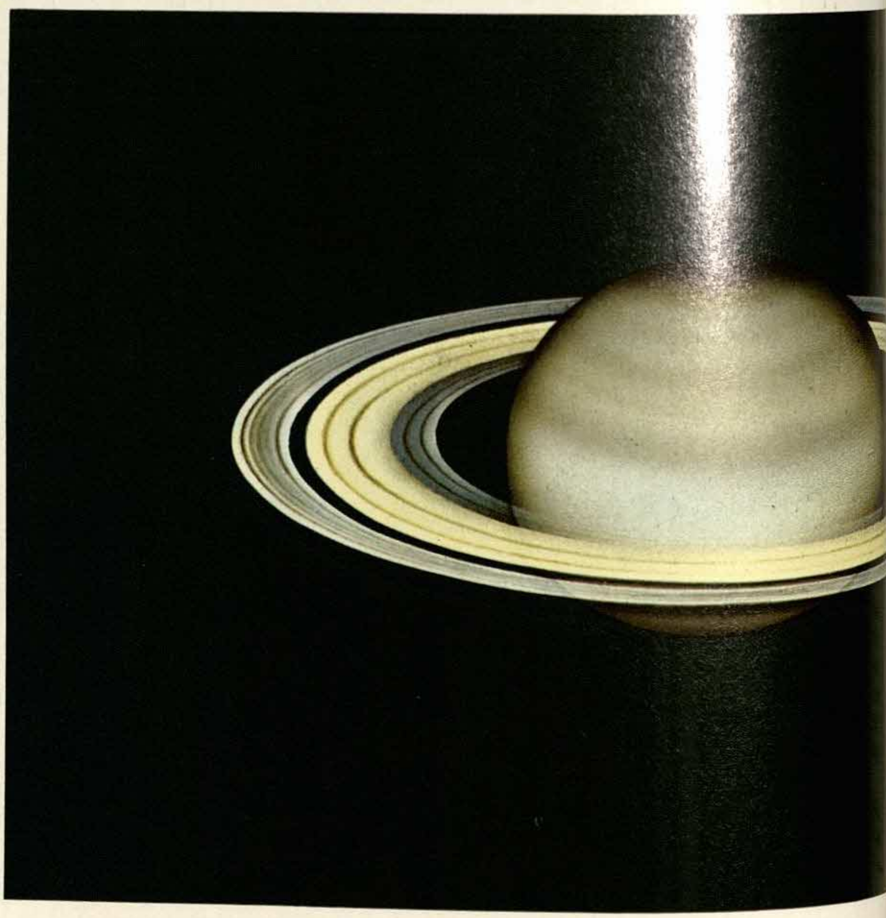

saw an extremely large ring around the planet. In 1675 the Italian astronomer G. D. Cassini, with a still more powerful instrument having a resolving power of 1″ (one second of arc), noted that the ring was divided into two parts separated by a dark streak (subsequently named Cassini's division). Later, with the advent of more powerful telescopes, it was discovered that Saturn has three rings.

THE COMPOSITION OF SATURN'S RINGS

The question of what exactly Saturn's rings are made of has occupied generations of astronomers. By spectroscopic observation, it has been determined that the rings rotate. Astronomers cannot see markings on the surfaces of the rings that would prove a rotary movement; however, as in studies of the sun, spectroscopic analysis has established both the fact and the speed of rotation. It has been demonstrated that the rings do not rotate as a rigid body, but that the ring nearest the planet rotates more rapidly than that farthest away. The variation in speeds is consistent, and the difference in speed indicates that each ring rotates independently of the others. It has been observed, moreover, that the more

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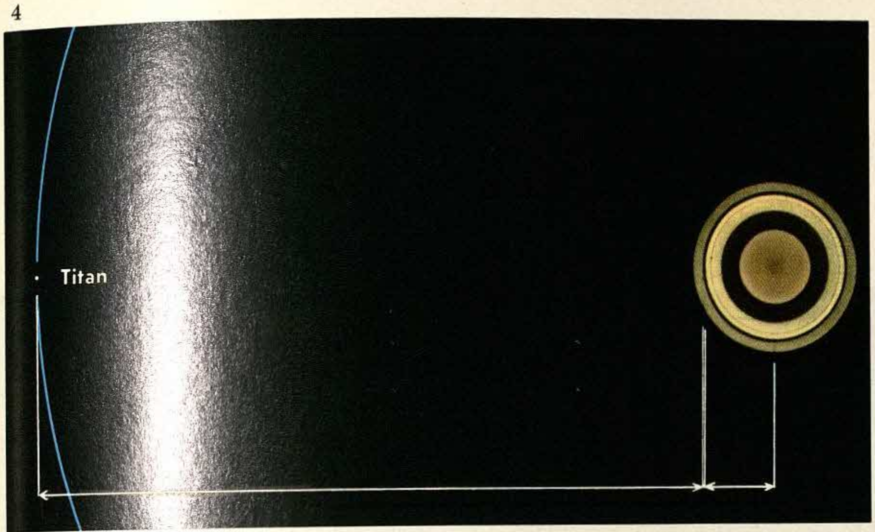

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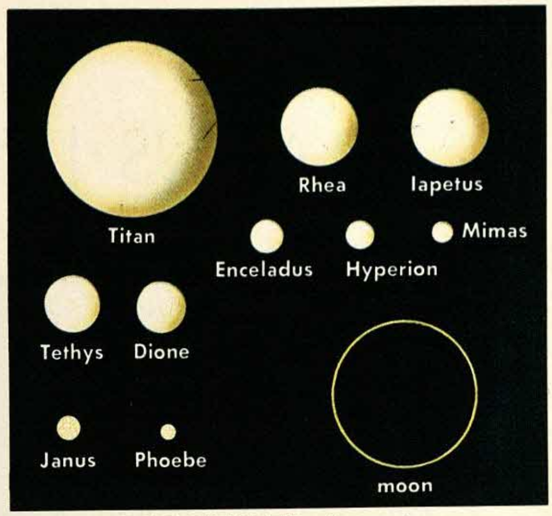


SATELLITES AND RINGS—A satellite whose period of rotation is exactly divisible by the period of rotation of a particle in the ring causes a dispersion of the particles of which the ring is composed and effects a division.

THE SIZE OF THE SATELLITES—As can be seen, one of Saturn's satellites is larger, and the rest are smaller, than the moon.

obliquely Saturn's rings are struck by the sun's rays, the less intense is the light reflected from the rings. This variation in light intensity can be explained by the assumption that the rings are composed of gravel and ice particles—that is, particles of light-reflecting solid matter, rotating around the planet like a swarm of asteroids and meteorites. It could be said that no other planet is surrounded by so many tiny "moons" as is Saturn.

SATURN'S SATELLITES

Like Jupiter, Saturn has a large number of satellites, ten in fact. They form a less extensive system than Jupiter's but, nevertheless, have several important characteristics. Jupiter has four satellites of almost equal brightness (with a great gap in brightness between them and the others), which are visible only with special instruments. Saturn, on the other hand, has satellites whose brightness decreases progressively, beginning with the largest—Titan—which is visible through a small telescope. The following table, which sets out the particulars of Saturn's satellites, shows at a glance that many of the planet's satellites are observable through a small telescope. Some of these —Iapetus, Rhea, Tethys, Mimas, and Hyperion—are about tenth magnitude.

The exact diameters of these satellites are necessarily uncertain because of their immense distance from the Earth. However, their masses have been determined with considerable accuracy because of the mutual gravitational attraction exercised by the satellites on one another.

SATURN'S SATELLITES

name	discoverer	year	distance from Saturn's center, km	visual magnitude	diameter, km
Janus	Dollfus	1966	160,000	14.0	300
Mimas	Herschel	1789	185,000	12.1	480
Enceladus	Herschel	1789	240,000	11.8	640
Tethys	G. D. Cassini	1684	290,000	10.3	970
Dione	G. D. Cassini	1684	380,000	10.4	970
Rhea	G. D. Cassini	1672	530,000	9.8	1,290
Titan	C. Huygens	1655	1,220,000	8.4	4,830
Hyperion	W. and G. Bond; W. Lassell	1848	1,480,000	14.2	480
Iapetus	G. D. Cassini	1671	3,560,000	10.1 to 11.9	1,130
Phoebe	W. H. Pickering	1898	12,950,000	16.5	160

The satellite having the largest mass—about twice that of the moon—is Titan. The smallest is Mimas.

TWO EXCEPTIONAL SATELLITES

The satellites Titan and Phoebe have unusual characteristics. Titan is the largest of Saturn's moons; while its size does not equal Jupiter's Ganymede, it is larger than Callisto, Io and Europa. A spectroscopic analysis of Titan's light reveals that the satellite's atmosphere is rich in methane; calculation proves that it is possible for this type of atmosphere to remain on the satellite only if its temperature is close to the temperature of Saturn—about −150° C (−238° F).

Phoebe, remarkable for its retrograde motion, rotates around Saturn in a direction opposite to that of the other satellites—and opposite to the direction the planets revolve around the sun. Jupiter's eighth and ninth satellites also move in a counterclockwise direction. This peculiarity of motion leads to the assumption that these satellites are captured asteroids.

Many of Saturn's satellites show periodic variations in brightness that correspond to the time taken to rotate around the planet. Therefore, it is likely that they have surface markings that are always visible, and that these satellites always show Saturn the same face—just as the moon does the Earth. The widest variation in brightness is that of Iapetus, which appears more than five times brighter when it is west (to the right) of Saturn than when it is east.

URANUS | Herschel's "comet"

On the night of March 13, 1781, the amateur English astronomer William Herschel made a major discovery—the planet Uranus. Using a homemade 7-in. reflecting telescope, Herschel had been carrying out a systematic inspection of every star and nebula he could find in the sky. While focusing on a region in the constellation of Gemini that night, he observed a fuzzy, greenish object larger than a star. Curious about the nature of this new celestial body, he observed it again on the following evening, and noted that it had moved from its original position.

Herschel concluded from his observations that this was an object that moved within, or close to, the planetary system. Though he had not yet determined its exact nature, Herschel announced that he had discovered a new comet, and asked other astronomers to help determine its orbit.

THE NEW PLANET

After a year of observation and calculation, the orbit was found to be almost circular—unlike the long, narrow, elliptical orbit of a comet. The object was obviously a new planet, with an orbit beyond that of Saturn. It was named Uranus, in honor of the Greek god who personified heaven.

As more and more of the orbit of Uranus was observed, it became evident that Herschel had not been the first to see this planet. Examination of astronomical records showed that Uranus had been seen and noted by astronomers twenty times in the hundred years before Herschel's discovery. Each time, its position had been noted, and it had been listed as a star. Using these previous position notations, astronomers were able to determine the entire orbit of the planet with increasing precision.

THE ORBIT OF URANUS

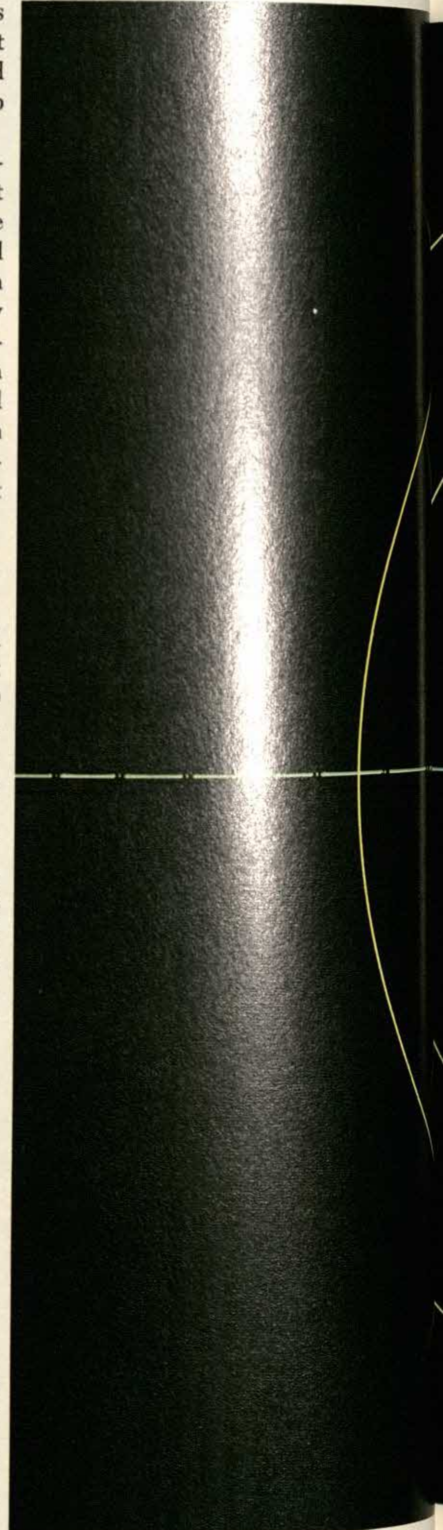
Calculation of the orbit of Uranus showed that it revolves in an elliptical orbit at 2,869,500,000 km (about 1,783,000,000 mi) mean distance from the sun. The difference between its maximum and minimum distances from the sun is more than

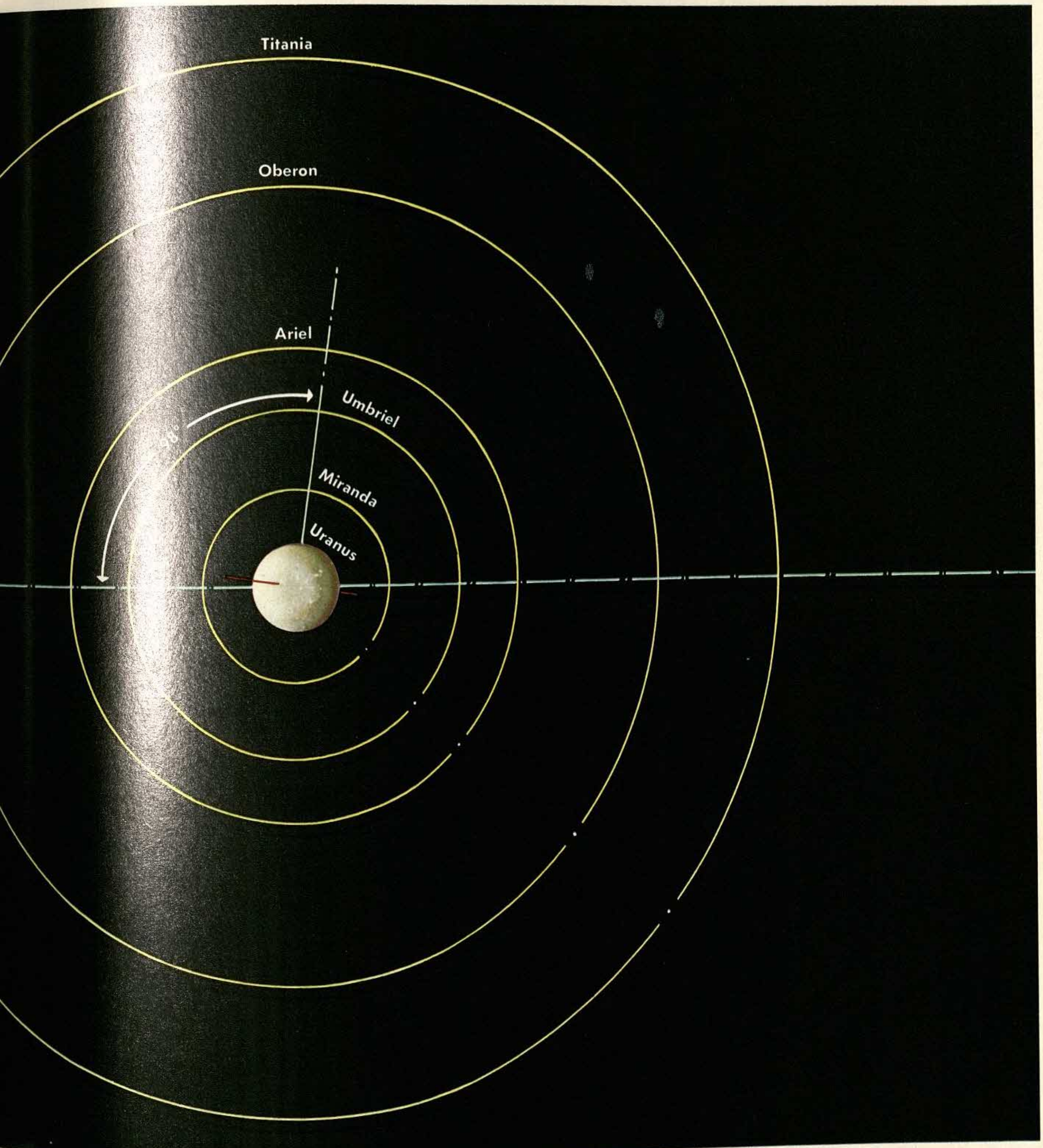
1

URANUS — This view (Illustration 1) shows a few details — the planet's greenish-gray color, and very faint clouds and faint bands parallel to the equator.

URANUS' SATELLITE SYSTEM—The five satellites rotate at a 98° angle of inclination to the planet's plane of revolution about the sun.

2




Titania
Oberon
Ariel
Umbriel
Miranda
Uranus
98°

271,000,000 km (about 168,000,000 mi)—greater than the distance between the Earth and the sun.

Uranus rotates on its axis every 10 hours and 49 minutes and orbits the sun approximately once every 84 years. The axis of rotation is nearly in the plane of the ecliptic rather than nearly perpendicular to the ecliptic, as for most other planets. Since Uranus moves in such a large orbit, the relative distance of the greenish planet from the Earth varies little. Its luminosity is, for all practical purposes, the same, no matter where it is observed. Uranus shines like a star of the sixth magnitude, and can be observed with the unaided eye, once its position is known.

URANUS THROUGH THE TELESCOPE

Details on the surface of Uranus are difficult to view through the telescope. The planet has approximately the same luminosity as Jupiter's satellites, and appears as a small, greenish disk in the amateur's telescope. It has an equatorial diameter of 46,700 km (about 29,000 mi)—about 3.6 times that of Earth; its distance from Earth is so great, however, that it receives about 350 times less of the sun's light than does the Earth. Such a poorly lit subject does not easily reveal its details.

Major telescopic examination has revealed surface spots similar to, although less obvious than, those seen on Saturn. The disk of Uranus is quite elliptical, and its poles are measurably flattened. The short rotational period of the planet probably accounts for this polar flattening.

The visual magnitude of Uranus at mean opposition is 5.44, according to the photoelectric measures made by H. L. Giclas at the oppositions of 1950, 1951, and 1952. (Opposition is a configuration in which one celestial body is opposite to another in the sky or in which the difference in longitude is near or equal to 180 degrees). All published observations of Uranus from 1864 to 1932 led W. B. Becker to the conclusion that there was a well-defined variation in the brightness of Uranus, having a period of 8.4 years and a visual amplitude of 0.31 magnitudes. From observations made between 1936 and 1947, J. Ashbrook also found evidence for an eight-year period. From his photoelectric measurements of 1950 to 1952, however, Giclas found no variations in brightness; neither did he detect any short-term variations that could be ascribed to the rotation of the planet.

The first visual observation of the dark bands in the spectrum of Uranus apparently was made by the Italian Jesuit and astrophysicist Angelo Secchi in about 1870. Several pioneers in astronomical photography made photographs of the spectrum of Uranus in the last quarter of the 19th century. In 1909 V. M. Slipher published a series of photographs of the spectra of the planets from the violet to the limit of the visual red. The spectra of the giant planets show dark absorption bands that grow stronger progressively from Jupiter to Neptune. The bands are so strong in the spectra of Uranus and Neptune that they absorb most of the light in the yellow, orange, red, and infrared regions. This accounts for the bluish-green tint of these planets. The substance that produces this absorption remained unknown until 1932, when R. Wildt showed that the most prominent planetary markings occur at the positions of bands of ammonia and methane observed in laboratory spectra. Wildt's work was later confirmed and extended by A. Adel and Slipher at the Lowell Observatory, Flagstaff, Arizona, and by W. S. Adams and T. Dunham, Jr., at Mount Wilson Observatory, near Pasadena, California. The bands of ammonia are more prominent in the spectrum of Jupiter but are much weaker in Saturn, probably because of its lower temperature. On Uranus and Neptune, with a surface temperature of about −200°C (−328°F), the ammonia is probably frozen out leaving only the methane.

COMPOSITION AND STRUCTURE

Spectroscopic studies of Uranus has confirmed the planet's rotational velocity and has provided information about its mass, its density, and the chemical composition of its atmosphere.

The spectrum of Uranus, like the spectra of other major planets, reveals an atmosphere containing large amounts of methane and ammonia. The volume of Uranus is about 70 times that of Earth, and its mass a little more than 14 times that of our planet, indicating a density of 1.6 times that of water, which is approximately the same as the other major planets.

THE SATELLITES

Six years after his discovery of Uranus Herschel detected two of its satellites now known as Titania and Oberon. They rotate in a retrograde motion, at a 98° angle of inclination to the plane of the planet's orbit. The planet's axis of rotation, however, is inclined by about the same amount, so that the plane of rotation of the satellites is nearly coincident with the equatorial plane of Uranus.

In 1851, the English astronomer William Lassell discovered two more satellites, Ariel and Umbriel, which were also shown to have a retrograde motion. These four major satellites have diameters of only a few hundred kilometers or in the case of Titania, about 1,100 km (about 680 mi).

In 1948, the Dutch-American astronomer Gerard Peter Kuiper used an 82-in. reflecting telescope to photograph the area surrounding Uranus in order to compare the luminosities of the four satellites. A fifth image appeared in the photograph, and further investigation showed it to be a minor satellite having very poor luminosity. It was named Miranda.

NEPTUNE | the twilight planet

The enthusiasm aroused by the discovery of the planet Uranus in 1781 was somewhat dampened in the years that followed, when astronomers realized that they could not predict the planet's movements with precision. Uranus never appeared exactly where their calculations indicated it should be.

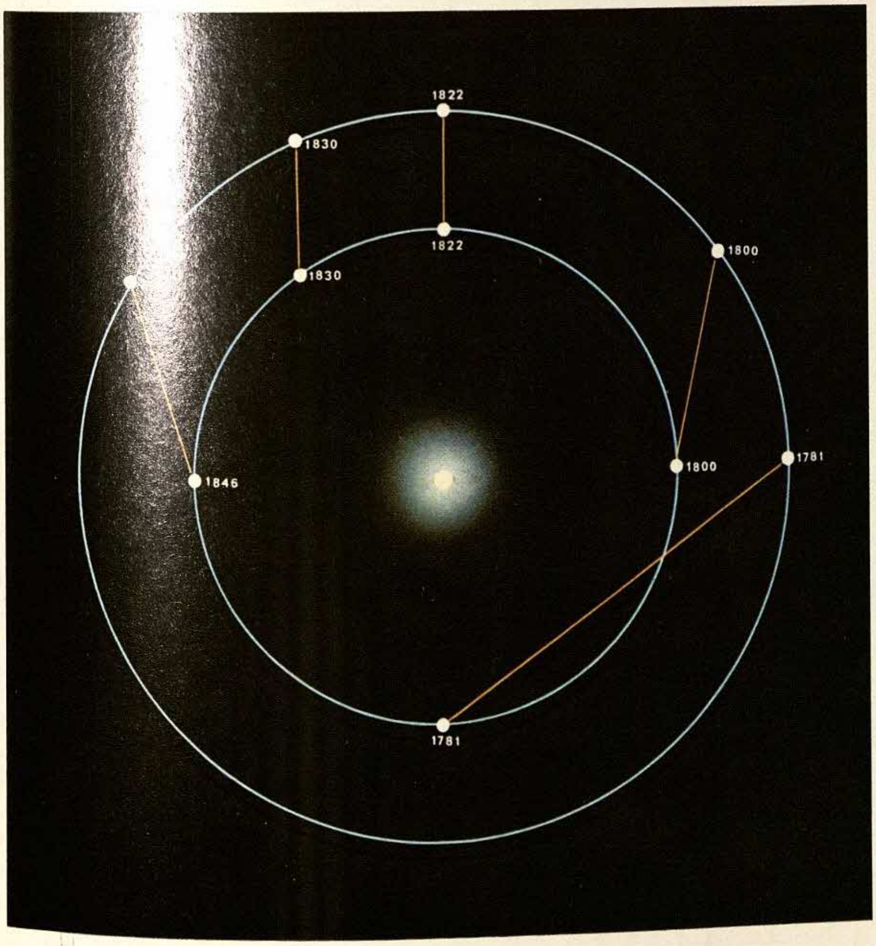
Working backward, astronomers reconstructed the planet's earlier movements, basing their work on 17 chance observations made between 1690 and 1781 by men who saw the planet but thought it was a fixed star. These observations showed further irregularities.

In 1820, the French astronomer Alexis Bouvard constructed detailed tables of the movements of Jupiter, Saturn, and Uranus, allowing for mutual perturbations—the gravitational force the planets exert on each other. For Jupiter and Saturn these tables proved correct, but for Uranus they were unsatisfactory.

There was, of course, a possibility of error in the recorded observations of Uranus. As years passed, however, and more observations were made, it became increasingly clear that the deviation of the planet from its proper orbit was actual and not a result of observational error. On the supposition that the calculations had been wrongly based, the astronomers looked for new factors: different positions of the perihelion, different eccentricities of the ellipse. They found nothing to account for the discrepancies.

URBAIN J. J. LEVERRIER—This French astronomer is credited with the "desk discovery" of the planet Neptune. After he completed his theoretical calculations, the German astronomer Johann Galle confirmed the position of the planet by observation.

HOW NEPTUNE INFLUENCED URANUS, 1781–1846—As seen from the Earth, Uranus (on the inner blue circle) appeared ahead of or behind where astronomers expected it to appear. The orange lines show the direction of the perturbative effect of the unknown planet Neptune (on the outer blue circle) in different years.

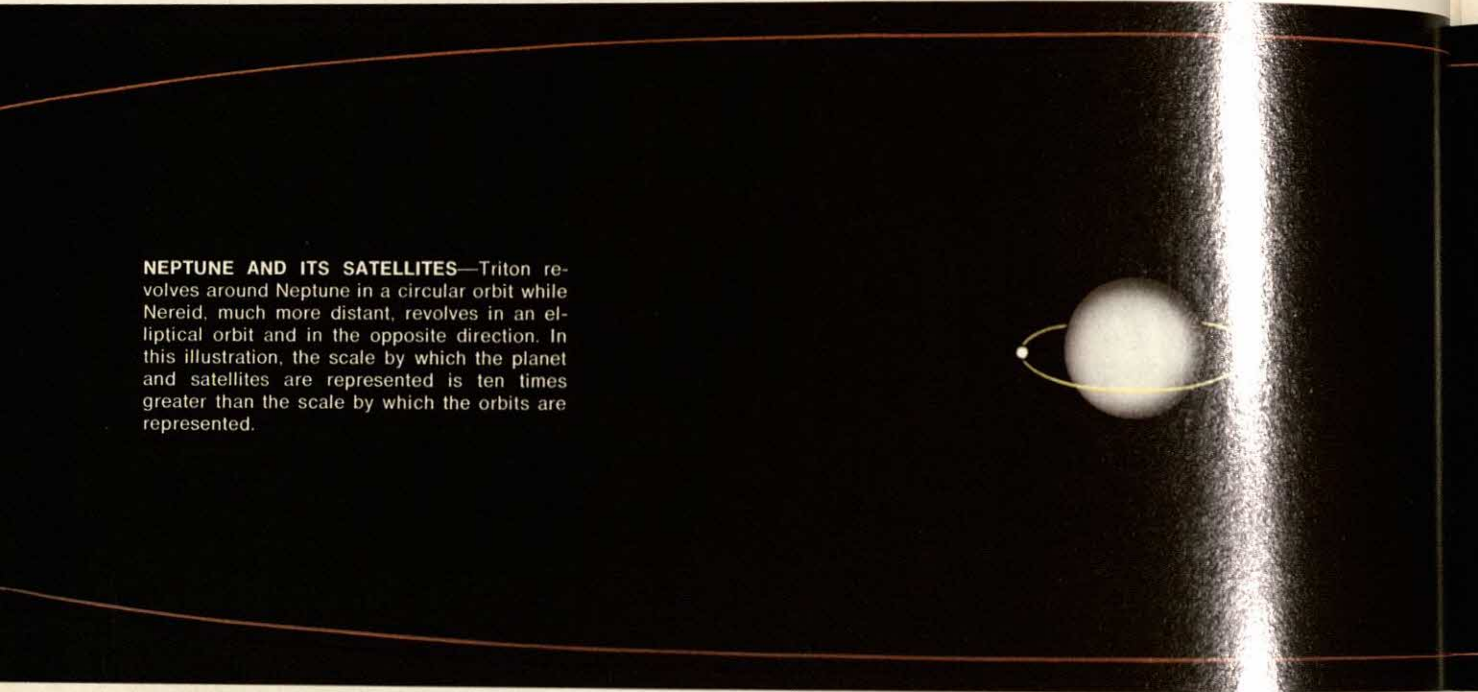


Two hypotheses could be advanced: either Newton's mechanics, which had shown that it was possible to predict the movement of any planet with absolute accuracy, were wrong; or some unknown and invisible perturbative body was causing Uranus to deviate from its predicted path. Of the two hypotheses, astronomers found it easier to accept the latter. By the early 1840s, astronomers in several different parts of the world were convinced of the existence of another planet beyond Uranus.

THE DISCOVERY

In Paris, the task of determining where to look for the unknown planet was undertaken by a brilliant young astronomer, Urbain J. J. Leverrier. After a relatively brief period of study, Leverrier concluded that the planet should be visible, through a telescope, in the constellation of Aquarius near the celestial longitude of 326°. He communicated this information to the French academy and to Johann Galle, then chief assistant at the Berlin Observatory.

On the night of September 23, 1846, Galle began a telescopic search of the area of the sky indicated by Leverrier. The search was unsuccessful. Then another astronomer suggested referring to a very complete star map that had re-



NEPTUNE AND ITS SATELLITES—Triton revolves around Neptune in a circular orbit while Nereid, much more distant, revolves in an elliptical orbit and in the opposite direction. In this illustration, the scale by which the planet and satellites are represented is ten times greater than the scale by which the orbits are represented.

cently been completed at the Observatory. When the men compared the stars on the chart with those visible in the sky, they found one star of the seventh magnitude that was not on the chart.

On the following night Galle again examined that part of the sky. He found that the new star had moved a distance equal to that forecast for the unknown planet. The mystery was solved, and a new planet had been discovered.

Meanwhile, a similar investigation was being carried on in England. At Cambridge University and at Greenwich Royal Observatory, John C. Adams calculated, independently of Leverrier, where the unknown planet should be. Late in 1845, Adams communicated the results of his work to Sir George B. Airy, director of the Greenwich Observatory, and to James Challis of the Cambridge Observatory. At Airy's suggestion Challis began a telescopic search, but he used a slow method: he planned to remeasure and remap all the stars in the indicated area of the sky, and to confirm his work by repeating his observations. He would then compare the two charts to see if any star had changed position. If Challis had not waited to complete all his observations before drawing the stars on his charts, he might have discovered the new planet before Galle did. Challis actually observed Neptune on August 4, 1846, but he did not realize that it was the new planet he was looking for.

The search for the new planet seems to have been carried out with an air of calm detachment rather than excitement, perhaps because the astronomers were so certain of the existence of the planet. It is said that Leverrier felt no particular desire to look through a telescope and actually see the planet whose position he had predicted.

CRITICISM OF THE DISCOVERERS

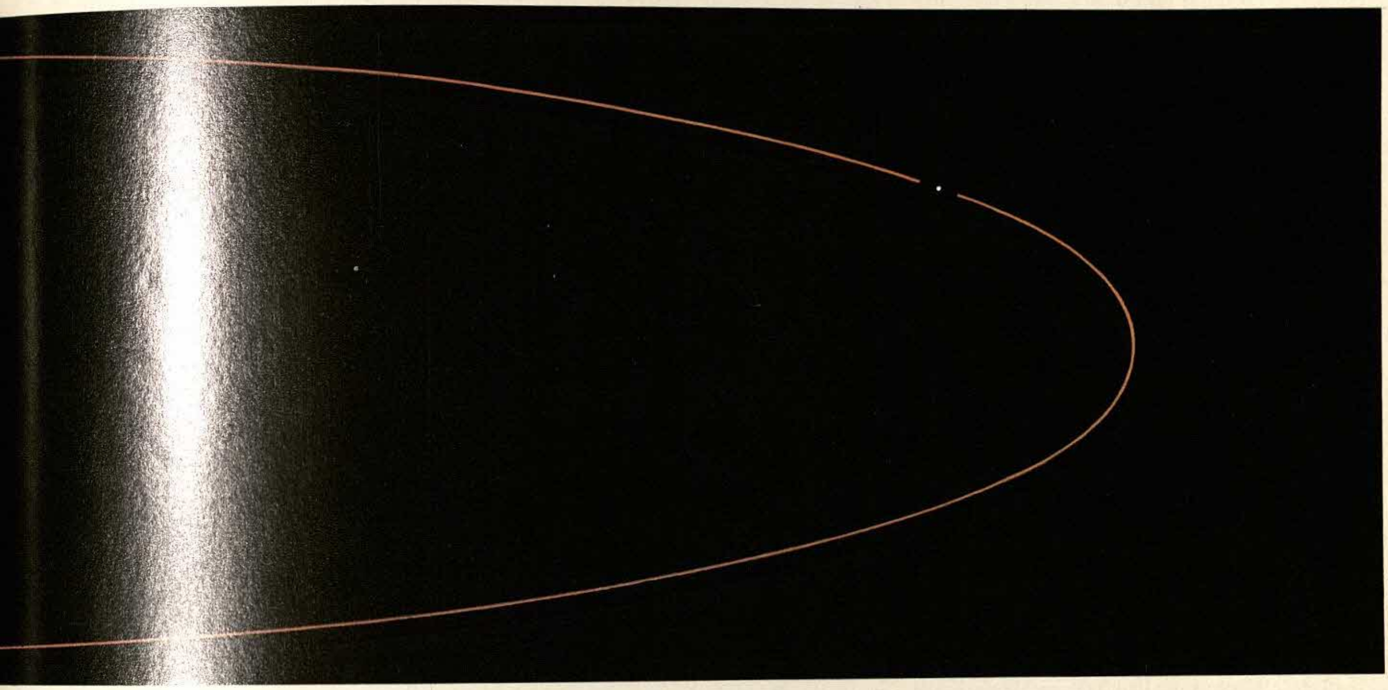
Scientists everywhere received news of the discovery with great enthusiasm. Never before had an important discovery been predicted by a "desk scientist," who worked, not with a telescope and other complex instruments, but with pencil and paper.

Unfortunately, considerable bickering developed between the institutions and nations involved, concerning who was to receive credit for the discovery. Leverrier's calculations were made public first, but Adams' calculations turned out to be more nearly correct. The orbit of Neptune proved to be more nearly circular than Leverrier had predicted, and the mean distance of Neptune from the sun much less than he had thought possible. Some astronomers even suggested that the calculations furnished by both Leverrier and Adams were so full of errors that the discovery should be considered accidental. This view was not well founded, however, as the methods followed by the calculators were the best available at the time, and the actual sighting of Neptune was the direct result of Leverrier's work.

The French astronomer D. F. Arago wanted to name the new planet Leverrier, but this suggestion met with little favor outside France. Arago later proposed the name Neptune, which was adopted.

THE ORBITING OF NEPTUNE

Neptune revolves around the sun at a mean distance of about 2,797 million miles, about 30 times that of the Earth. Neptune's period of revolution is about 164.8 years. Because this orbit is so large, the sun as seen from Neptune would be only as large as Venus seen from the Earth; the human eye would perceive only a strongly luminous point. The light that Neptune receives from the sun is only 1/900 of the light the Earth receives; yet it is still 500 times greater than the light the Earth receives from the full



moon. Daylight on Neptune would be like twilight on Earth.

MASS, SHAPE, AND DIMENSIONS

Neptune's mass, which has been determined with precision because of the two satellites that revolve around it, is 17.3 times that of the Earth. In order to estimate density it is necessary to know the planet's size. Attempts to measure the disk visible through a telescope produce a value higher than the actual one. All early determinations were carried out in this way, and for a long time Neptune was thought to be somewhat larger than Uranus. When the diameter is measured with stellar interferometers, a value slightly less than the actual one is obtained, because the planet is darker at the edges than in the center. Astronomers have concluded that the diameter is 44,417 km (about 27,600 mi), as compared to about 47,000 km (about 29,300 mi) for Uranus. From this, it has been deduced that the density of Neptune is about 0.45 that of the Earth, as compared to 0.3 for Uranus. As the differences between the two large bodies that revolve near the limits of the solar system are small, astronomers often refer to Uranus and Neptune as the twin planets.

Neptune is so far away that it is impossible to see any surface markings on it, or to measure any flattening at the poles. It is possible by other means, however, to estimate both velocity of rotation and polar flattening. The shape of the planet affects the orbit of the satellite that revolves around it, and by observing this perturbation and measuring it, astronomers have estimated the amount of polar flattening and equatorial swelling. The equatorial swelling is caused by the rotation of the planet, and its amount depends on two factors: the velocity of rotation and the distribution of density inside the planet. Astronomers believe that the internal composition of Neptune is similar to that of Jupiter and Saturn, since the density is similar. A computation of these factors and the results of spectrographic observation indicate that Neptune's period of rotation is about 15.8 hours.

NEPTUNE'S SATELLITES

Seventeen days after the discovery of Neptune, the English astronomer William Lassell discovered the satellite Triton a little less distant from the planet than the moon is from the Earth. Triton's luminosity is that of a 13.6 magnitude star; its diameter is about 4,000 km (about 2,500 mi). Triton revolves once around Neptune at a mean distance of 354,200 km (220,000 mi) in about six days, following a circular orbit with retrograde motion; that is, in the direction opposite to the direction Neptune rotates on its axis.

In 1949 a Dutch-American astronomer, Gerard Peter Kuiper, undertook photographic research in order to discover the possible presence of other satellites. This led to the discovery of a second body, the satellite Nereid, which has the luminosity of a 19.5 magnitude star. Nereid moves in a strongly elliptical orbit in the same direction as Neptune's rotation, opposite to the direction Triton moves. This led astronomers to believe that Nereid is a satellite recently captured by Neptune rather than a satellite born with the planet.

Nereid revolves around Neptune in a period of 359.4 days. The mean distance or length of the semimajor axis of the satellite's orbit is 5,578,650 km (or 3,465,000 mi), but the eccentricity of the orbit is so high (0.76) that Nereid may approach as close as 1,339,520 km (832,000 mi) to Neptune and recede as far as 9,821,000 km (6,100,000 mi). Kuiper estimated that Nereid is 180 mi. in diameter and 1/4,000 as massive as Triton (which has 0.22 times the mass of the Earth or 1.8 times the mass of the Earth's moon).

PLUTO | a difficult discovery

From that night in 1609, when Galileo first turned his telescope on the heavens, astronomers have discovered three more planets in the solar system. The first of these discoveries was made in 1781 by Sir William Herschel, who observed a strange celestial object moving in a consistent pattern. The object was the planet Uranus, some 2,869,500,000 km (about 1,783,000,000 mi) from the sun.

With the discovery of Uranus, it seemed—at least for a few years—that man had probed to the farthest reaches of the solar system. Continued study of the orbit of Uranus, however, revealed perturbations that convinced astronomers that one or more unseen planets existed farther out in the solar system. This conviction was proved correct in 1846 when the English mathematician John Couch Adams and French astronomer Urbain Leverrier, working independently, discovered the planet Neptune, orbiting approximately 1,700,000,000 km (about 1 billion mi) farther from the sun than Uranus. Encouraged by this discovery, astronomers began a systematic probing of the skies in search of still another planet that they believed moved even beyond Neptune's orbit.

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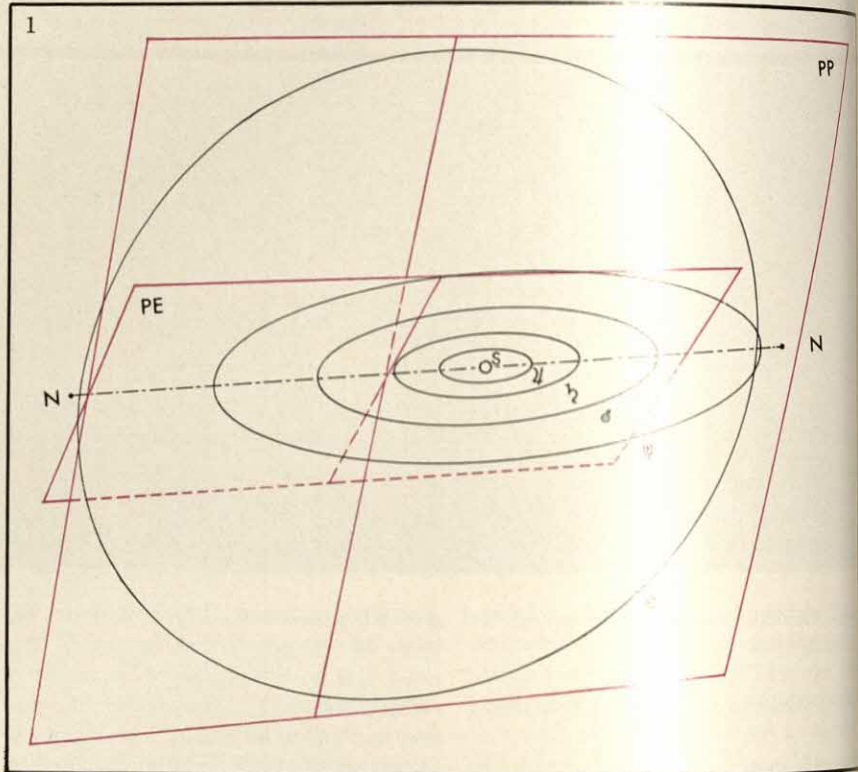

A STRONGLY INCLINED ORBIT—Pluto's orbit lies on a plane inclined about 17° with respect to the plane of the Earth's orbit, the greatest inclination of any planetary orbit. This fact has led to the theory that Pluto may be a lost satellite of Neptune. The perturbations caused by the unknown planet on its neighbor Neptune were extremely difficult to calculate; as a result, the photographic search for Pluto was made over a vast area of the sky.

In this illustration, PP is the plane of Pluto's orbit, PE the plane of the Earth's orbit. For reasons of clarity, the inclination between the two planets has been exaggerated; NN is the line of intersection (line of nodes) between the planes of the two orbits. The illustration shows, as can be seen also in Illustration 2, that at one point in its orbit, Pluto comes closer to the sun than Neptune.

THE DIFFICULTY OF THE NEW UNDERTAKING

The problem was difficult. First of all, there was the substantial difficulty of observation, because any planet beyond Neptune would be so far from the sun that it would have little of its reflected brilliance. The search must be made among many faint stars rather than among those that shone as brightly as Neptune. In fact, there were some 20,000 stars of about the same brightness as Neptune (the actual number studied was considerably less, inasmuch as the search for Neptune was restricted to a small area of the sky). In the search for another planet beyond Neptune, however, calculations indicated that the new planet might be found anywhere in a vast area of the sky.

A second major difficulty lay in the fact that calculations could not provide any accurate clues to the unseen planet's probable location: Bode's law could not help in predicting the planet's distance from the sun, because the law had proved unreliable in the search for Neptune. Furthermore, astronomers suspected that the planet's orbit would be drastically inclined in comparison with the orbits of the other planets. The search, therefore, would have to be concentrated far above or below the ecliptic—the projection of the plane of the Earth's orbit onto the celestial sphere.

Finally, the perturbations influencing Neptune were by no means as obvious as those exerted by Neptune on Uranus—an important factor that had aided Adams and Leverrier in their discovery.

THE FIRST SEARCHES FOR THE UNSEEN PLANET

The search for Pluto began late in the nineteenth century, when not all the difficulties mentioned above were fully realized. The first visual search took place in 1880 at the Washington Naval Observatory, with a 65-cm (about a 26-in.) telescope. At that time, photography had not yet been used as a tool in astronomical research.

The American astronomer David Todd began the search on the assumption that (1) the unknown body had a slightly larger diameter than Neptune; (2) that it was never more than one degree above or below the ecliptic; (3) that it traveled

around the sun at a distance 52 times greater than the Earth's; and (4) that the planet was on a point of the ecliptic between longitudes 146° and 148°. According to these predictions, the planet should have a diameter of about 2 seconds of arc and a magnitude of 13. In a relatively short time, Todd had checked the positions of about 5,000 stars. In spite of his careful search, however, he was unable to locate the planet.

In 1919, a search for the unseen planet was made at Mount Wilson Observatory (California) using more accurate calculations than had been available to Todd, and employing photographic apparatus with a 25-cm (about a 10-in.) lens. Several photographs were taken of the area of the sky where the planet should have been, according to the calculations, but the search was futile.

In 1930, when the planet Pluto was finally detected and its orbit calculated, astronomers checked the position it should have occupied eleven years earlier, at the time of the 1919 search. The planet was found on the photographic plates at Mount Wilson, where ten years before astronomers had found nothing.

RESEARCH AT LOWELL OBSERVATORY

At the beginning of the twentieth century, photographic techniques had advanced sufficiently to permit the use of photographs in the search for the new planet. Calculations, which predicted the position of a celestial body influencing Neptune, were made with enough accuracy to encourage a large-scale search. However, few observatories wanted to devote a major share of their time and talents to such a limited project; only at the Lowell Observatory in Arizona was an exhaustive search made. This search, which lasted from 1929 to 1945, had as its objective not only the discovery of the unseen body influencing Neptune but also the location of any other unknown objects, such as asteroids, that might be revolving around the sun outside Saturn's orbit.

THE INSTRUMENT USED IN THE SEARCH

Before undertaking the search for Pluto, Lowell Observatory technicians constructed and mounted a special photographic lens with a diameter of 32.5 cm (about 13 in.) and a focal length of 169 in. This lens produced extremely clear images on plates of 35 x 43 cm (about 14 to 17 in.). A one-hour exposure recorded the presence of stars of about magnitude 18.

When the instrument was pointed away from the Milky Way, a one-hour exposure recorded about 40,000 stars. Near the Milky Way, the number of stars on each plate reached the million mark. In the plates in which Pluto finally was discovered, the number of stars totaled nearly 400,000.

THE SEARCH FOR PLUTO

Innumerable devices were employed to locate the position of a celestial body that calculations had predicted with great uncertainty. Three positive plates were made of each area of sky. The same area was then rephotographed after a time. Three plates were used to assure accuracy. Comparison of the two sets of photographs would reveal the movement of any celestial body. This comparison was made with a blink microscope, a basic instrument, until about 30,000 stars a day were being checked.

THE DISCOVERY OF THE PLANET PLUTO

On February 18, 1930—in a pair of plates that reproduced an area of sky near the star Delta in the constellation of Gemini—the Lowell astronomer Clyde Tombaugh finally found the new planet. Another camera had photographed the same area of sky on the same night and it, too, had revealed the planet. On February 19, still another photograph of the area was taken as a check on what had already been recorded; and in this photograph, the new planet had moved as much as could have been predicted from

ECCENTRICITY OF PLUTO'S ORBIT—Pluto's elliptical orbit is so eccentric that only the orbits of some asteroids are more unusual. This diagram of the external part of the solar system shows that Pluto comes closer to the sun than Neptune. The intersection of the orbits of these two planets is only apparent, however, because—due to their respective inclinations—the points of intersection are formed by lines on different planes. (The diagram is limited to Jupiter, Saturn, Uranus, Neptune, and Pluto, because the orbits of the planets nearer the sun are too small to be seen. That of Mercury, for example, would be smaller than the disk of the sun.)

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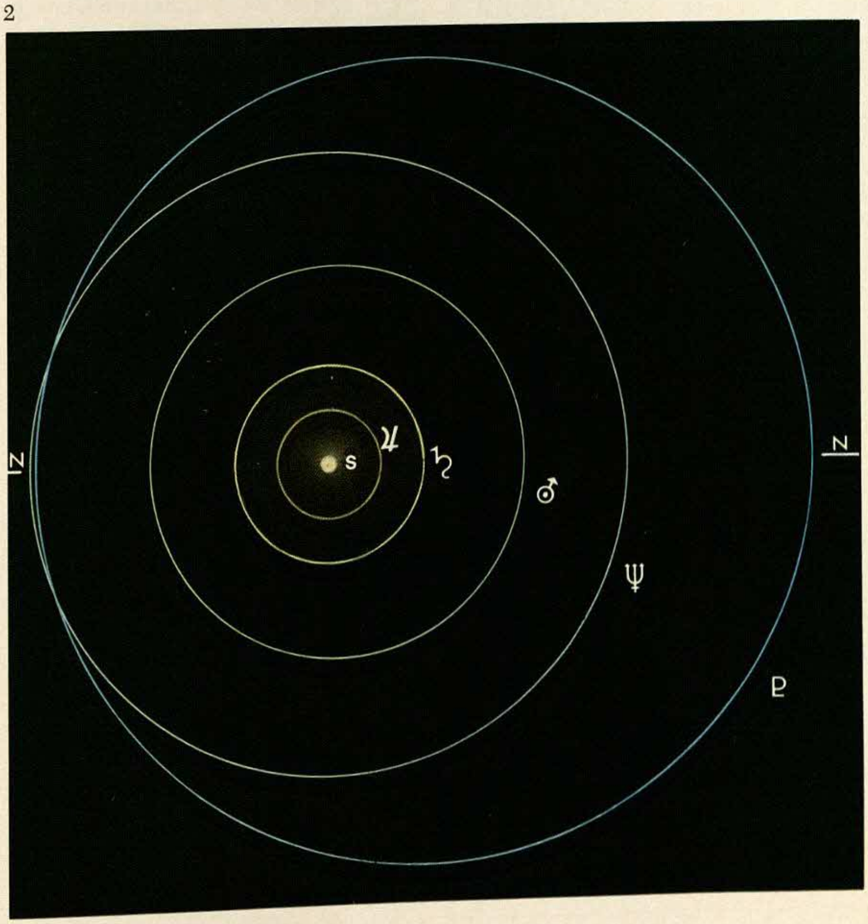

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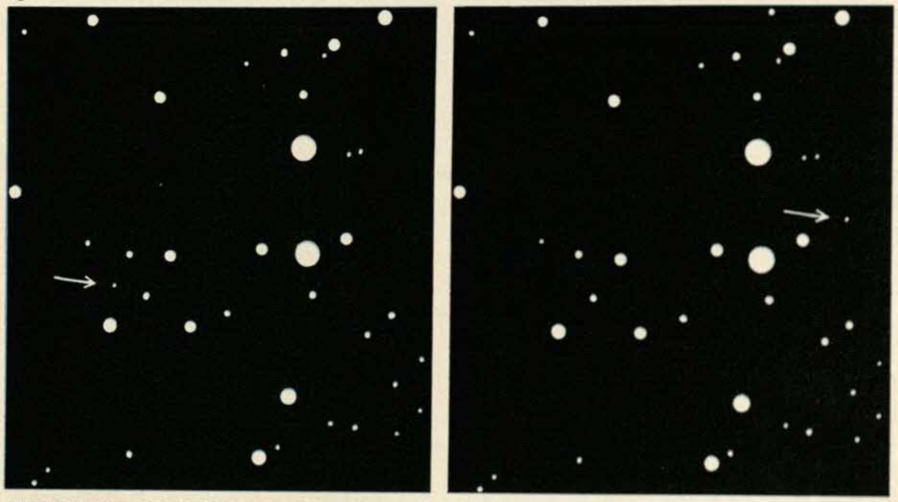

THE DISCOVERY OF PLUTO—On January 21 and 29, 1930, a pair of plates was exposed at the Lowell Observatory. Against the background of stars, an object was found that moved in a manner similar to that predicted for the planet that had been sought for years. The discovery of the new planet's existence was verified on February 18 and 19 of the same year when analysis of the plates was completed. The movement of Pluto across the sky is indicated by arrows in the illustration.

THE AREA COVERED IN THE SEARCH FOR PLUTO—This illustration shows, by means of a polar projection known as a planisphere, the area (shaded) in which astronomers looked for the unknown planet among stars as faint as magnitude 17. The dotted areas indicate where a search was made among stars as faint as magnitude 14. The sinusoidal line represents the ecliptic.

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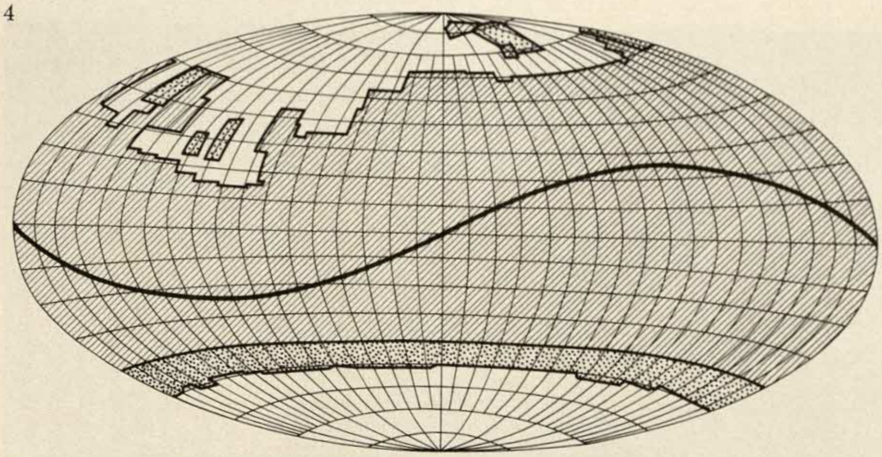

examining the plates of the previous night.

The large number of astronomers who immediately took up observation of newly discovered Pluto were disappointed. They had expected a planet having a magnitude of at least 13, but the new planet had a magnitude of 15. Furthermore, a comparison between the planet's visual appearance and its appearance on film disclosed that Pluto was very different from Uranus and Neptune. It had been thought that any new, distant planet would be similar to its two nearest neighbors, so that most astronomers did not at first believe a new planet had been discovered at all.

THE CONTINUATION OF THE SEARCH

The discovery of Pluto—which was announced on March 13, 1930—did not interrupt Lowell Observatory's major project: the search for other celestial bodies revolving around the sun beyond Saturn's orbit. Some were found, along with many other interesting objects—including a globular cluster, many open clusters, a cluster of 1,800 galaxies, a comet, 145 new asteroids, and about 1,807 variable stars. Besides these, the images of 29,548 extragalactic nebulae were recorded on the plates.

THE NEW PLANET

Clyde Tombaugh, the discoverer of the planet, and his colleagues chose the name of Pluto for the new body. This tiny world circles the sun once every 248 years in an eccentric orbit that is inclined about 17° with respect to that of the Earth. Pluto's mean distance from the sun is about 3.6 billion miles, yet at perihelion, which will occur in 1989, Pluto will come closer to the sun than Neptune does. Although the two planets' orbits cross each other, Pluto cannot collide with Neptune because of the extreme inclination of its orbit. The eccentricity of Pluto's orbit has led some astronomers to believe that Pluto once was a satellite of Neptune, breaking away in the early days of the solar system to travel on its own distant orbit.

After considerable difficulty, Pluto's diameter has been established at approximately 5,000 km (about 3,700 mi). Its mass is thought to be about 0.1 that of the Earth's. If this is so, its density must be very high. The brightness of Pluto varies about 10 percent in a period of 6.39 days, indicating that its surface is not uniformly bright and that the planet rotates once every 6.39 days. Since knowledge of this planet is very limited, however, exact values have yet to be established.

PLANETS BEYOND PLUTO?

The Schmidt telescope, invented in 1931, provided astronomers with an entirely new optical system for use as a wide-angle camera. With such instruments, advanced research may be carried out in the future. The major difficulty in searching for additional planets is the identification of very faint bodies among hundreds of millions of stars. Before Pluto was discovered, the Lowell Observatory examined 90,000,000 stellar images. In the future astronomers may discover even smaller bodies, either nearer or farther away than Pluto's orbit.

PATHWAYS TO SPACE | beyond the Earth's atmosphere

The modern science of astrophysics may be considered as having passed through three phases. The first phase began when astronomers learned how to analyze light from the stars by attaching spectrographs to their telescopes. The second phase, extending from the beginning of the present century until World War II, was characterized by an abandonment of narrowly classical research on the part of astronomers, and their concentration on the physical aspects of astronomy, particularly by constructing special instruments such as large reflecting telescopes. The third and most recent phase is distinguished by the direct exploration of space, promising possibilities that were previously beyond imagination.

The scope of astronomical investigation that can be carried out from the Earth's surface is limited because the atmosphere interferes seriously with telescopic observation. The nature of the surface of the moon or planets can best be investigated by reaching these locations. Even the stars can be observed more efficiently from a spacecraft than from the Earth, for certain stellar radiations do not penetrate the Earth's atmosphere.

The actual exploration of space was necessarily preceded by considerable research into the problems involved in undertaking such exploration. The first stage was characterized by sending instruments into the upper atmosphere, where stellar spectra and sunlight could be more effectively analyzed than at the Earth's surface; in this way many new facts were discovered. Even more important results were obtained by placing the instruments in artificial satellites. In modern terminology, suborbital flights were followed by the orbital flights of unmanned satellites. The next phase was to use manned satellites, and to send both unmanned and manned spacecraft beyond the Earth's orbit, to the moon and the planets–the current phase. The next phase, which can be realized in a relatively short time, is the establishment of orbital and lunar stations. Plans were being formulated in 1970 for the development of an orbiting space station and a shuttle transportation spacecraft. The space station would be about 5 m (15 ft) in diameter and about 12 m (40 ft) long. Operating in near-Earth orbit, it would be

SUBORBITAL FLIGHTS—In this representation of the first 400 km (about 250 mi) of the Earth's atmosphere, the parabola represents the trajectory of a rocket's suborbital path. Such a rocket is launched almost vertically—that is, at an inclination of about 85°, and, therefore, has a very narrow trajectory that is a segment of an elliptical orbit. The range of the rocket's effectiveness for astrophysical observations is between 100 and 200 km (about 60 and 125 mi); below 100 km the atmosphere is too dense.

From ground level to 2 km (about 6,500 ft) the air is so dense that it holds dust particles and water droplets in suspension, especially under turbulent conditions, and so impedes such observations as that of the solar corona; for this reason the lowest level at which a coronagraph should be set up is generally recognized as 2,500 m (about 8,200 ft). This altitude is indicated on the illustration by the dot-and-dash line just above the ground. Coronagraphs are often installed at altitudes of 4,000 m (about 13,100 ft) or more in order to avoid the denser layers of the lower atmosphere. Even at this altitude, however, atmospheric turbulence seriously hinders astronomical observations. Inasmuch as the layers of air have different densities because of varying temperature and humidity, their perturbation gives a twinkling appearance to the stars and a waviness to images in a telescope—the latter detracting from the resolving power of the instrument.

At the end of 1950, during an interesting experiment, an observer was sent up in the pressurized cabin of a balloon to an altitude of about 30 km (about 18.5 mi). From this altitude, where the sky is so dark even in daytime that the planets are visible, the observer was able to study Mars telescopically under particularly favorable conditions—better than can be observed from the Earth's surface with a telescope much larger than the observer used—because at that altitude no atmospheric turbulence exists and the air layers do not have variable refraction indices that can distort an optical image. It is not practical, however, to carry large telescopes in balloons. Such experiments were superseded by others made with rockets and orbiting satellites.

One reason for making observations at altitudes of at least 100 km (about 62 mi) is that the rarefied atmosphere permits the observation of long-wave ultraviolet light. The Earth's atmosphere, and particularly its oxygen, screens out ultraviolet light with wavelengths shorter than 2,000 Å (Ångstroms); unfortunately the Lyman alpha line of the hydrogen spectrum is below this level (1,216 Å). Because most bodies in space are composed largely of hydrogen, the observation of this line in the spectrum is of fundamental importance; this is not possible from the Earth's surface or even from an altitude attainable by a balloon, but only from altitudes exceeding 100 km, attainable only by rockets and artificial satellites.

Weak x-rays are also detectable at altitudes exceeding 100 km. This kind of radiation comes from space, from certain sources associated with the history of supernovas, gravitational catastrophes, pulsars, and neutron stars. This is another reason for making observations from higher altitudes.

At altitudes exceeding 200 km (about 125 mi), it is possible to study the composition of the micrometeorites that fall out of space toward the Earth; below that altitude their spectrum is greatly changed by fragmentation. For that reason orbital flights were substituted for the earlier use of high-flying rockets that exposed an optically smooth but thin surface to the bombardment of these small particles.

Finally, the atmosphere is virtually undetectable at altitudes above 400 km (about 250 mi); all that can be detected is the solar wind, a stream of highly rarefied matter originating with the sun.

These, then, are the reasons that encouraged astrophysical researchers to go beyond the atmosphere in order to learn more.

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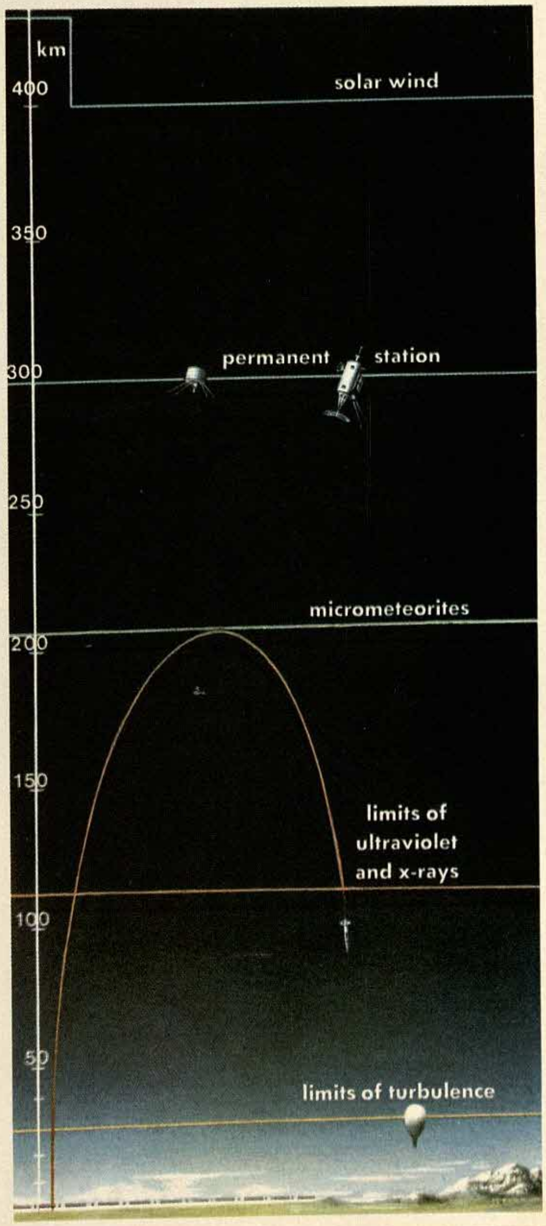

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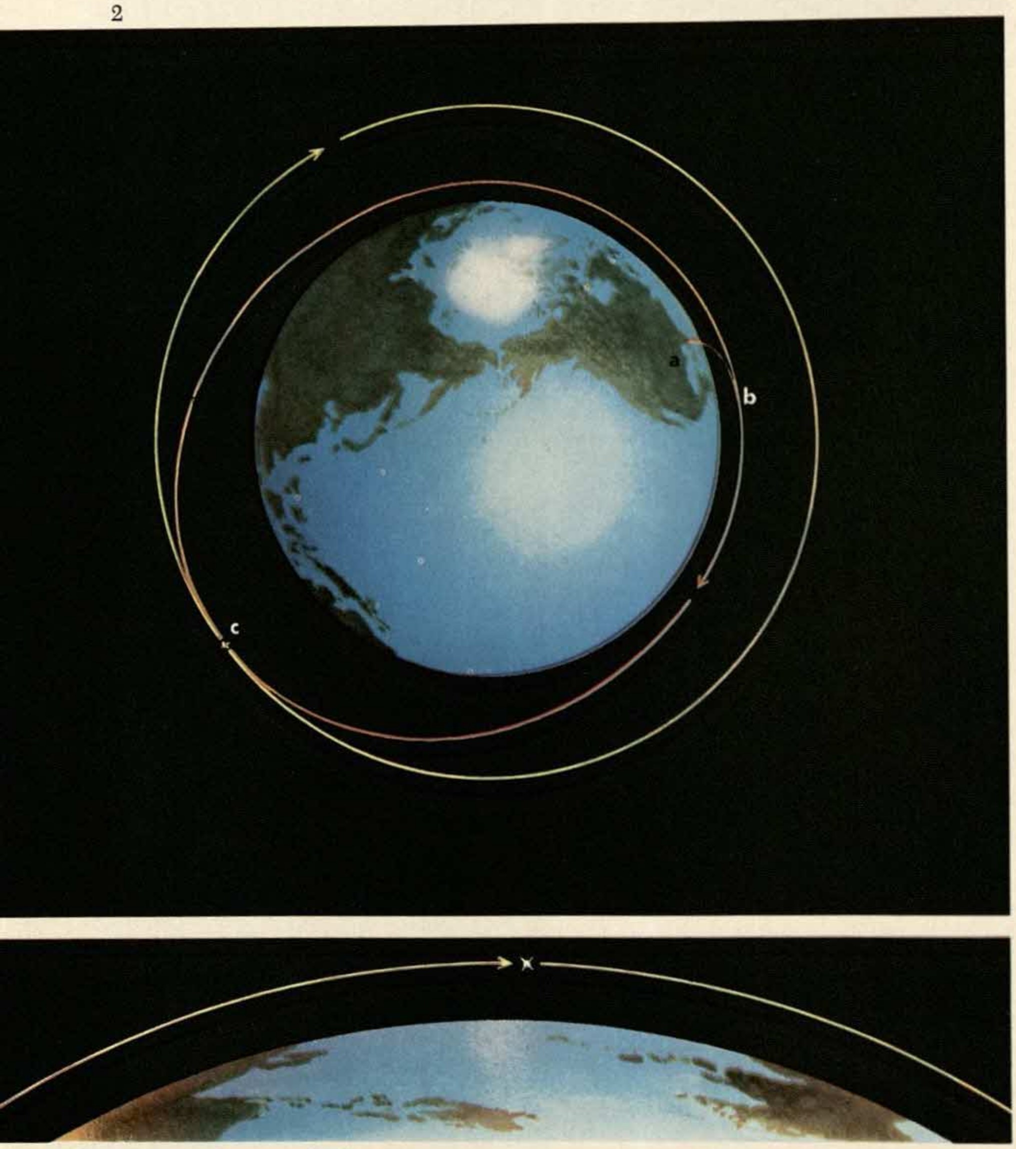
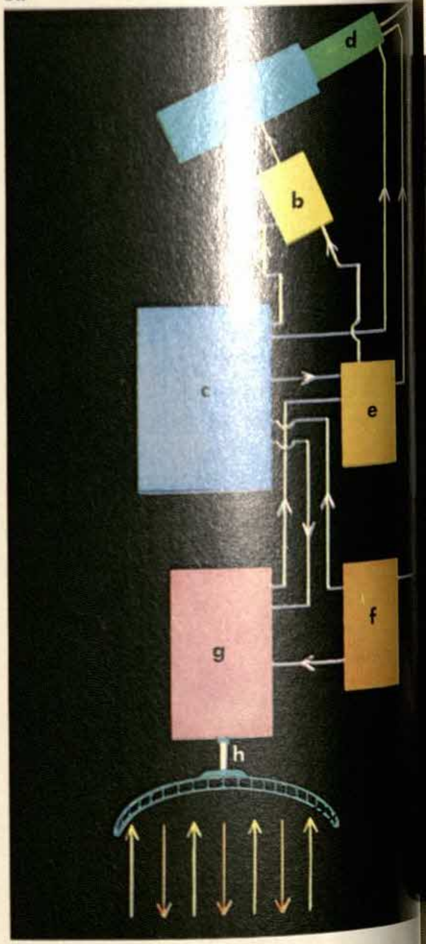


ORBITAL FLIGHTS — The upper illustration shows the path of an orbit around the Earth followed in certain astronomical expeditions. The rocket rises vertically from the launching site **a** and then, as its various stages are ignited, slowly tilts until it parallels the Earth's surface in circular orbit around the Earth. At a predetermined altitude **b,** the velocity is increased so that the circular orbit becomes an elliptical orbit, with **b** as its perigee (closest approach to Earth) and **c** as its apogee (the point most distant from Earth). When the satellite reaches apogee, jet thrusters are fired to increase the velocity once more so that the orbit again becomes circular, this time at the altitude of apogee—a more stable orbit, little influenced by terrestrial disturbances and suitable for a large number of orbits.

In the illustration the scale is not true; the orbit is shown much larger than it really is compared to the scale of the Earth. The actual orbit, which would be at an altitude of about 400 km (about 250 mi), is a rather small fraction of the Earth's diameter. The lower illustration, which shows a part of the curvature of the Earth, shows the orbital path in true scale.

UNMANNED ASTROPHYSICAL OBSERVATORIES—Illustration 3a is a schematic representation of a space observatory, of which many different types have been built. One of these, the Orbiting Solar Observatory (OSO), is used only to study the sun. As shown in Illustration 3b, OSO has a powerful telescope that picks up the sun's image and focuses it through the slit of a powerful spectroscope where it is analyzed. Another type is the Orbiting Astronomical Observatory (OAO), which has a system for training a telescope on in-

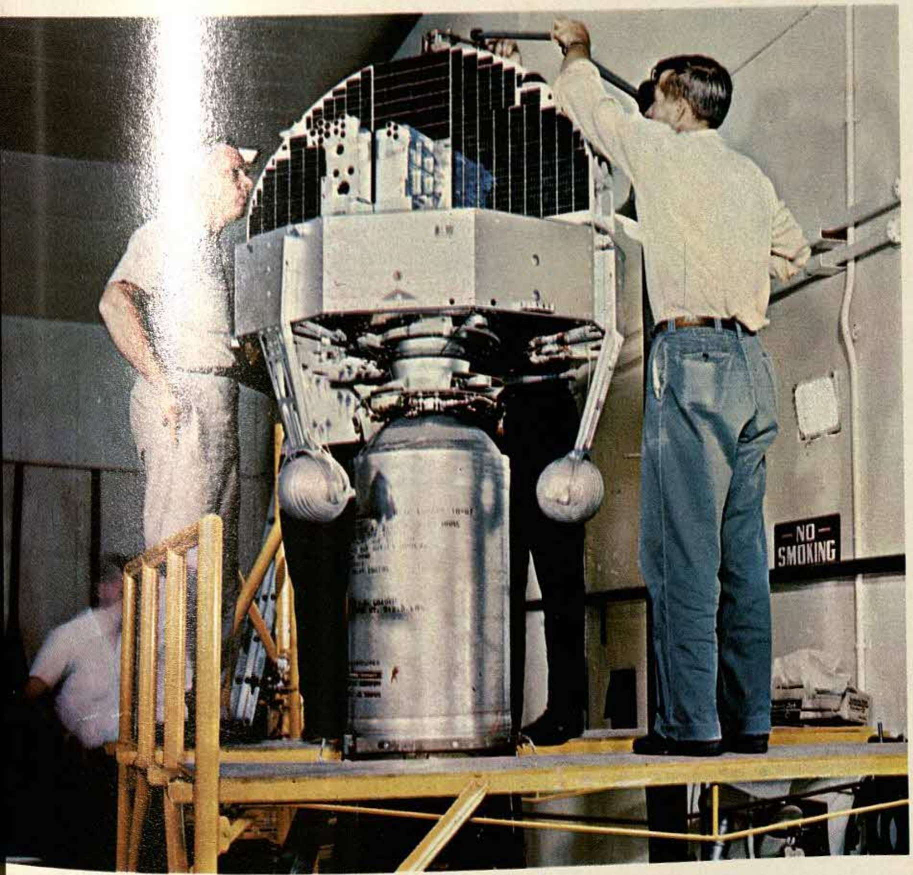
3a



dividual stars, the weaker light from which is similarly analyzed.

In Illustration 3a, the telescope is represented by the rectangle **a**; **b** is the system for training and stabilizing the telescope. These systems draw their energy from a complex of solar and storage batteries **c.** The solar batteries capture energy from the sun and the storage batteries store it for use when the observatory is in the Earth's shadow. A spectroscope and a spectrophotometer **d** are attached to the telescope, to analyze the light from the spectrum of the stars. Sometimes it is possible to record images or amplify light; this is accomplished with the aid of a computer **e.** It permits the observatory to make a predetermined series of observations. The computer is powered by the batteries **c** and commands the instruments **b** and **d.** A system is required to record information and transmit it to the Earth, for the satellite itself will eventually be destroyed by friction with the atmosphere; the system **f** contains magnetic tapes that are sent through a transmitter **g** over the parabolic antenna **h** to Earth. This system is also powered by the batteries **c.** A single OSO or OAO costs as much as the entire Mount Palomar Observatory.

3b



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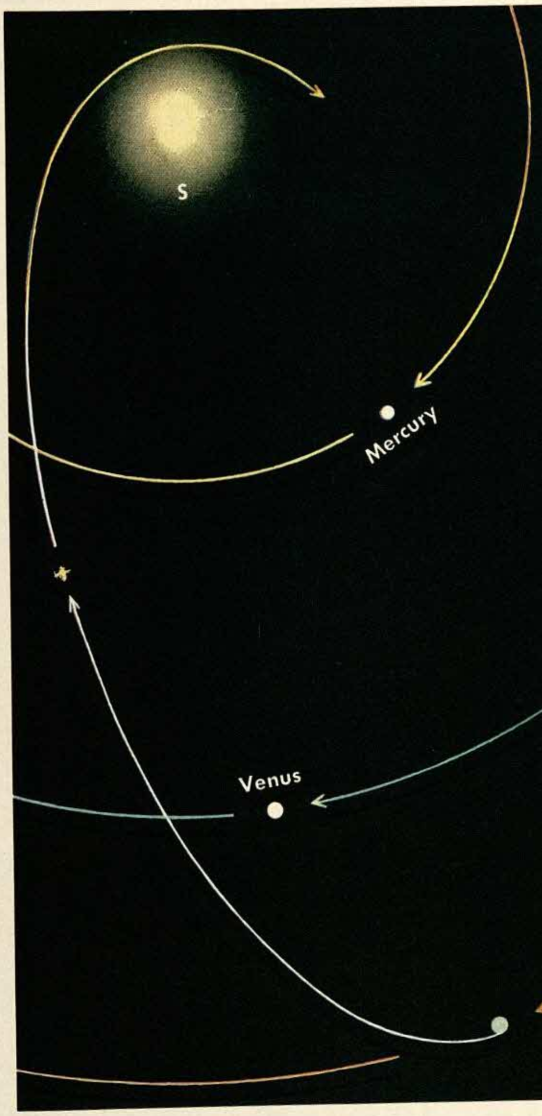
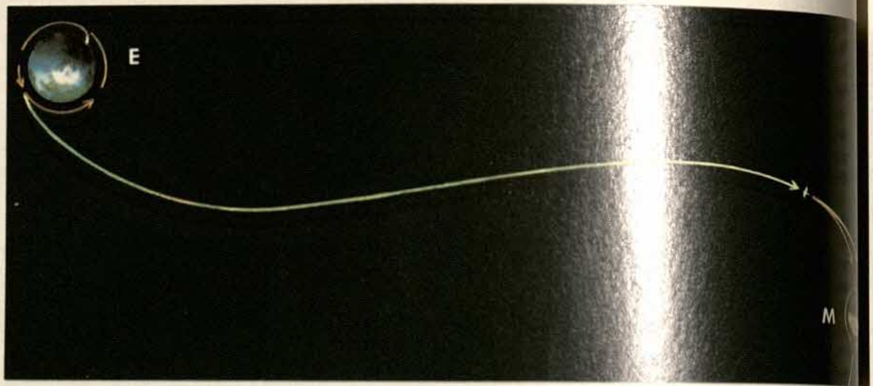


SOLAR PROBE—This illustration shows the path of a solar probe, in which a spacecraft crosses the solar system between the Earth's orbit and the sun. The purpose of such a probe is not to observe the sun more closely, for this would require an approach that would completely burn up the rocket. The purpose is rather to gather information about the magnetism, solar radiations, and magnetic fields in the vicinity of the sun. Such a probe is first placed in Earth orbit, then given escape velocity so that it approaches the sun along an elliptical orbit, with the sun as one of the foci of the ellipse.

PATHWAYS TO THE MOON—This illustration shows pathways between the Earth and the moon, starting with a launching from Earth, then a "parking" orbit around Earth, and an increase in velocity sending the spacecraft on its way to the moon. The Surveyor satellites traveled directly to the moon's surface, where they crashed after transmitting data to Earth. The Lunar Orbiters went into orbit around the moon. During moon orbit, local disturbances cause a satellite to pass over different parts of the moon's surface. During orbit, the spacecraft takes pictures that are recorded on videotape and transmitted to Earth.

5

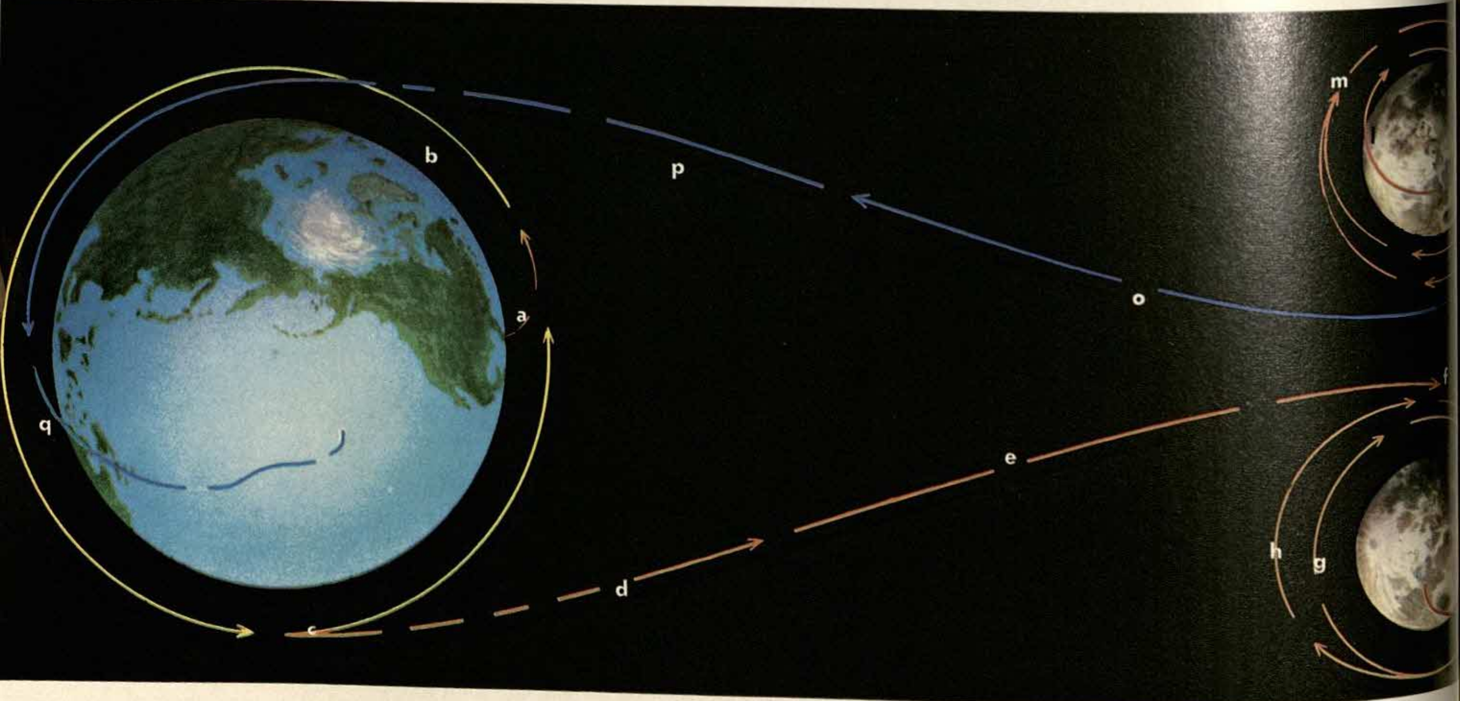


a center of various space studies. It would operate with a 12-man crew and could remain in operation for a 10-year period. Coming and going with large quantities of equipment and large numbers of passengers would be the shuttle transportation spacecraft. It was envisioned in the early 1970s as consisting of a completely reusable rocket-powered vehicle, including an orbiter and booster. After launch, the booster stage would carry the orbital stage out of the Earth's atmosphere, and the two would then separate. The booster stage would reenter the Earth's atmosphere and, through the use of its own jet engines, cruise to a horizontal landing at a prescribed place. The orbiter would proceed under its own power to an eventual rendezvous and docking with the space station. After the docking, the orbiter would separate and return to Earth for a horizontal landing. Both stages of the space shuttle could then be reserviced for launch within a two-week period. Operation of the shuttle was planned for the late 1970s. Both the station and shuttle would accommodate healthy persons with no specialized flight training.

The phases that would follow can only be speculative, and would depend on the advancement of techniques. It will require enormous velocity to send spacecraft to the stars, but preparations to accomplish this are on the drawing board at the present time.

MOON LANDING—Landing men on the moon is a complicated mission. The orbit is particularly intricate, and the rockets must be reignited several times in order to provide corrections of the trajectory, and to land and take off. The principal phases of the mission are illustrated: the launch into a parking orbit **a** and **b**; leaving the parking orbit **c** in the direction of the moon; mid-course corrections of the trajectory **d** and **e**; and a final correction **f** to enter lunar orbit, with the lunar module taking the course **g** and the command module remaining in orbit **h** as the lunar module lands **i**. The moon will have moved in its own orbit further around the Earth (hence the upper drawing of the moon) by the time the lunar module takes off **l** and rejoins the command module **m** for an orbit of the moon; the lunar module is then abandoned **n** and a rocket thrust sends the command module in the direction of Earth. Two mid-course corrections **o** and **p** are made en route; the command module descends **q** and lands in the sea.

6



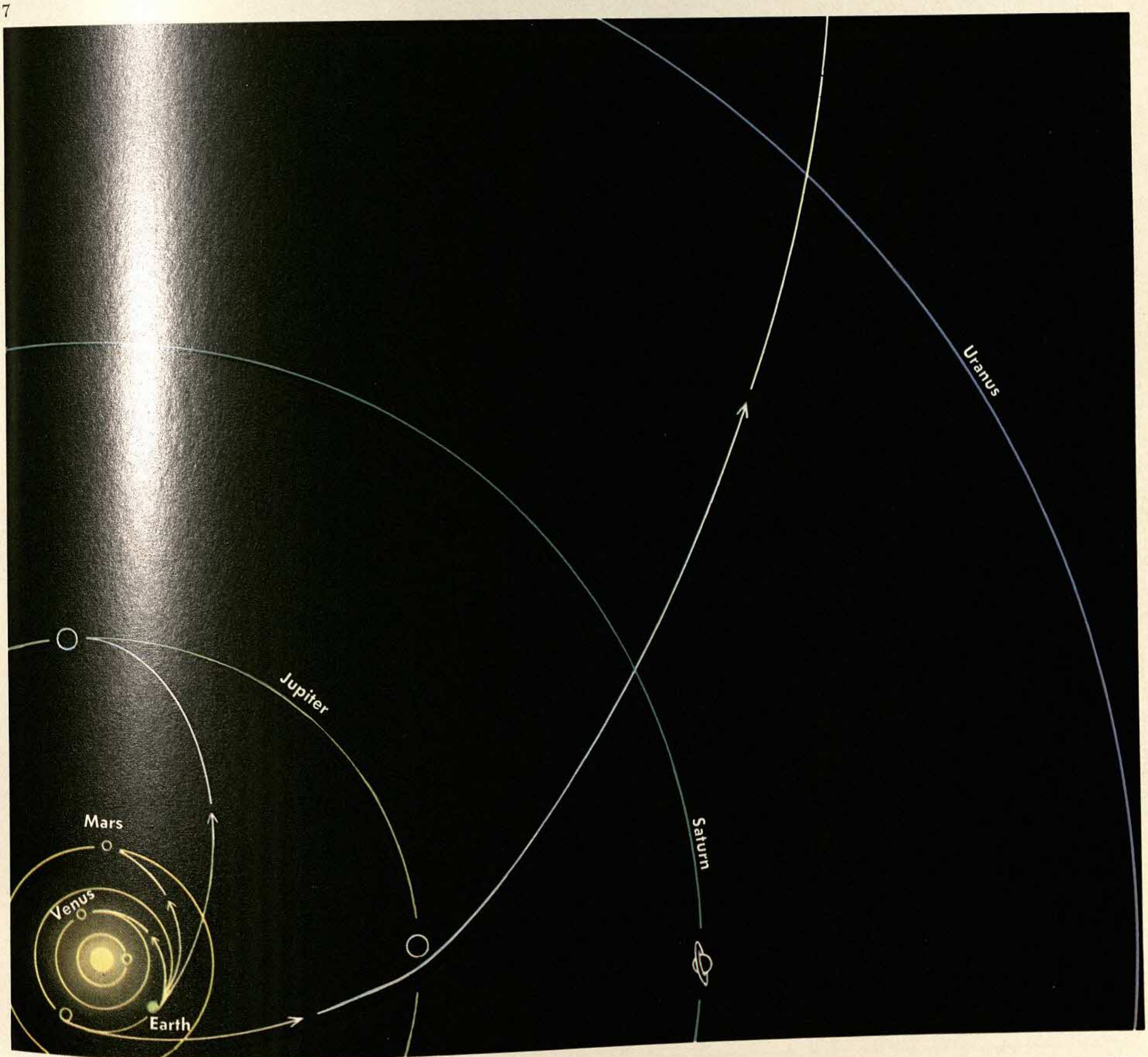
INTERPLANETARY MISSIONS—This illustration shows a part of the planetary system. When missions are sent to Venus or Mars, the rocket is first sent into parking orbit around the Earth; the orbit is then corrected to send the spacecraft in the direction of the target planet. The corrections give the satellite the least tangential energy with respect to the Earth orbit and the planetary orbit.

In the case of missions such as the Mariner probe toward Mars, the spacecraft passed the planet at a predetermined distance of more than 8,000 km (about 5,000 mi), because the instruments for observation worked effectively at this distance and the course did not present other problems. The Soviet Venus probes, on the other hand, carried the observation instruments close to the planet and set them down in a soft landing; the instruments continued to transmit data while passing through the heavy atmosphere of the planet.

Trajectories for reaching the outer planets (those shown on the diagram are Jupiter, Saturn, and Uranus) are more complicated. The trajectory toward Jupiter would be similar to that toward Mars, but much wider. In the case of the more distant planets, the time required to reach them would not be months, as for Mars and Venus, or years, as for Jupiter, but decades. A system described as a "planetary slingshot" has been devised to reduce these very long periods of time by sending the spacecraft along an orbit of minimal energy that will approach a target planet by a route alongside an intermediate planet. In the illustration, the spacecraft passes by Jupiter, is deflected (making its orbit slightly longer); the speed of the spacecraft is therefore greatly accelerated as it approaches the planet and decelerated as it passes on. Although the trajectory is somewhat longer, the flight time is shorter because of the increase in speed.

These are the trajectories that will be used in exploring the planetary system. Such explorations, however, may be decades in the future; and by that time space technology may have advanced to the point that nuclear energy will power the rockets. Unrestricted by minimal energy trajectories, such spacecraft could move under power for a large part of the route from the Earth to another planet, and interplanetary space could more easily be explored by man as the decades of flight time would be reduced to months or even weeks. Such explorations are so far in the future that speculation rather than prediction is involved in describing them.

7



ASTEROIDS | the discovery of the minor planets

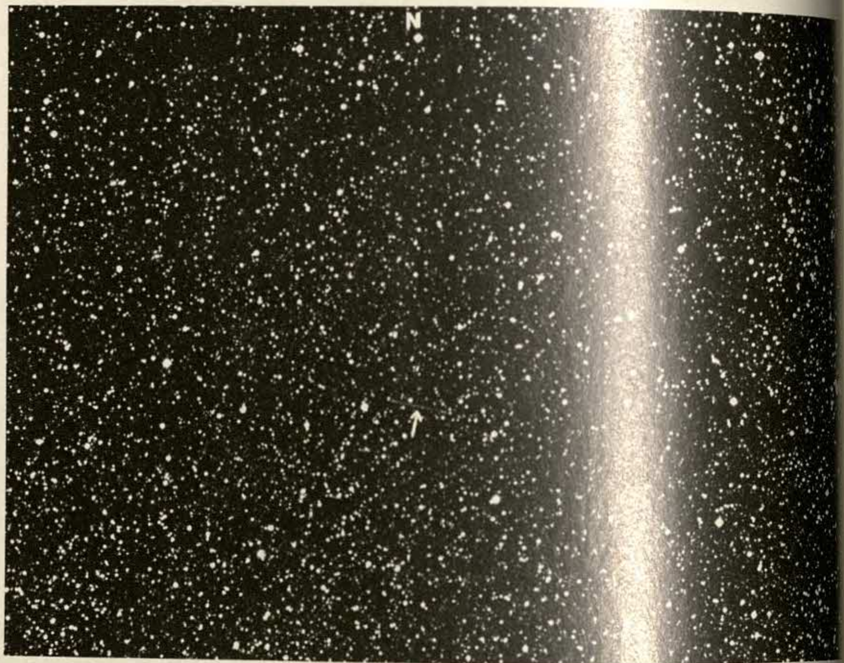
A diagram of planetary orbits has an order that is immediately obvious even to an untrained eye. This order, however, is disrupted by the gap between Mars and Jupiter, where a planetary orbit that would continue the regular spacing of the others is missing.

Johannes Kepler, in his studies of planetary motion in the early 1600s, had already noted this gap. The development of Johann Bode's empirical law nearly 200 years later strengthened the idea of the existence of another planet. Bode had discovered that the distances of the planets from the sun were proportional to a sequence of numbers obtained by adding four to the series 0, 3, 6, 12, 24, 48, 96 or, 4, 7, 10, 16, 28, 52, 100. From this sequence, the following series evolved: 0.4, 0.7, 1.0, 1.6, 2.8, 5.2, and 10.0. If the number 1.0 represents the distance between the Earth and the sun, the actual distances of the other planets from the sun are close to the other numbers. (The actual distances are expressed in astronomical units.)

planet	distance predicted by Bode's law	actual distance
Mercury	0.4	0.39
Venus	0.7	0.72
Earth	1.0	1.00
Mars	1.6	1.52
. . . . .	2.8	. . . . .
Jupiter	5.2	5.20
Saturn	10.0	9.54
(Uranus)	(19.6)	(19.18)

In 1781, when the planet Uranus was discovered, it was seen that it also revolved around the sun at a distance that corresponded accurately to Bode's empirical law. This particular circumstance convinced astronomers that between Mars and Jupiter another planet remained to be discovered. According to Bode's series, the distance of the undiscovered planet would correspond to the number 2.8—the gap in Bode's series. A great many astronomers began to devote themselves to the search.

1



THE PHOTOGRAPHIC TRAIL OF ICARUS— When an astronomer photographs a large stellar region, he often finds unfamiliar images on the film. These generally are meteorites or asteroids. In the photograph shown here, taken with the Mount Palomar Schmidt telescope, the faint trail of the asteroid Icarus is visible. Although many asteroids have been discovered by photographing a stellar region through which an asteroid is presumed to pass, this method has its limitations. Becau an asteroid moves relatively quickly acro the stellar field during the exposure peric only asteroids of considerable luminosity a registered. In order to register on film t light of a weaker asteroid, its presumed pa must be followed by a telescope so that light, concentrated in a fixed point, permi a time exposure.

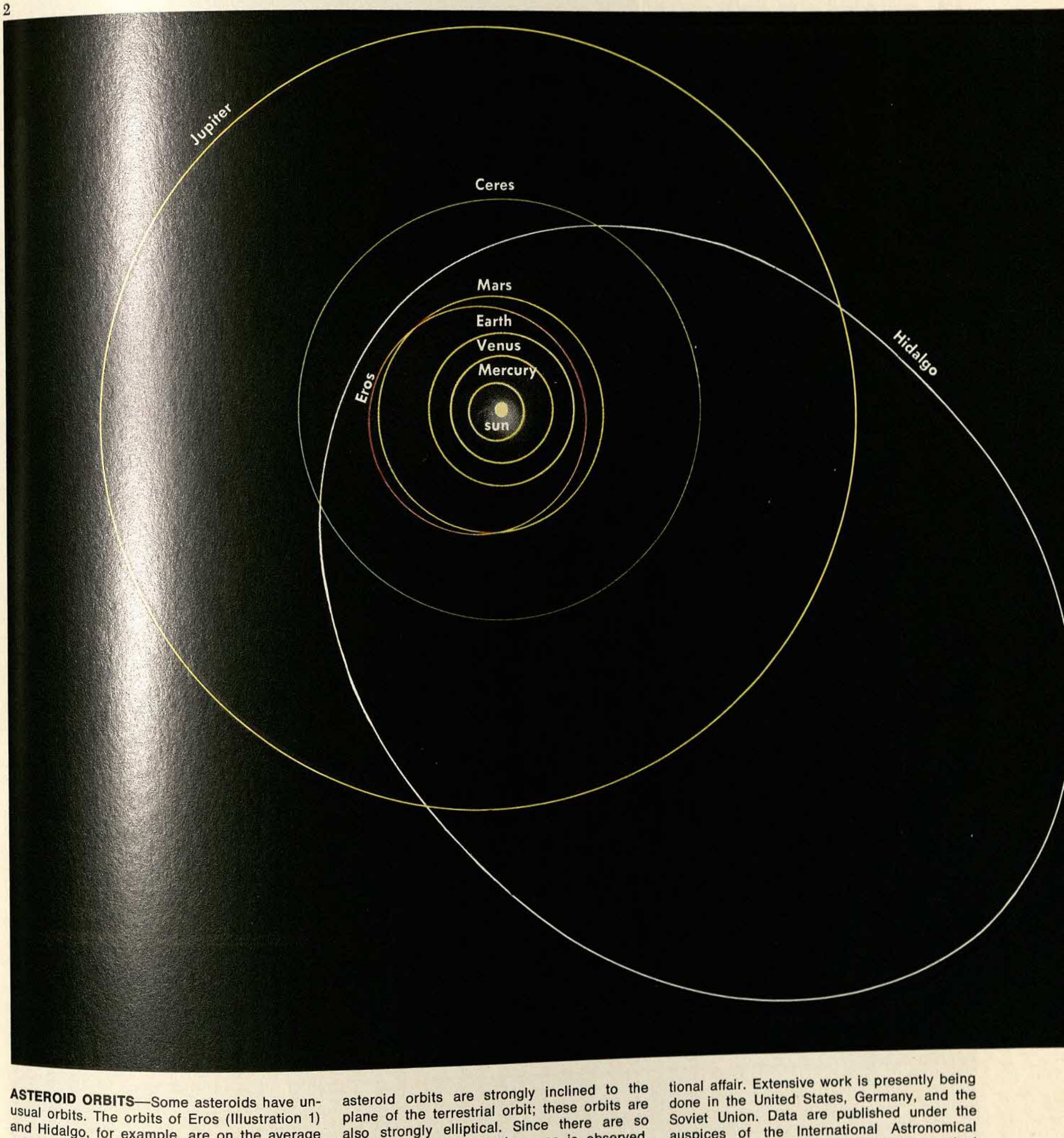
DISCOVERY OF THE ASTEROIDS

On New Year's Eve, 1801, the Italian astronomer, Giuseppe Piazzi, director of the Palermo Observatory, was observing a stellar area in order to complete a catalog of the stars near the ecliptic. The catalog would form the starting point for a search for the planet whose orbit was 2.8 in Bode's series. That night Piazza observed an object that, although quite bright, was not listed in previous catalogs. He fixed its position accurately, and, with the aim of improving his coordinates, he observed it again the next evening and found that it had moved.

Once he had determined the velocity of the celestial object in question, Piazza was certain that it had to be the missing planet between Mars and Jupiter. H gave the new body the name Ceres, afte the harvest goddess and divine prote tress of Sicily.

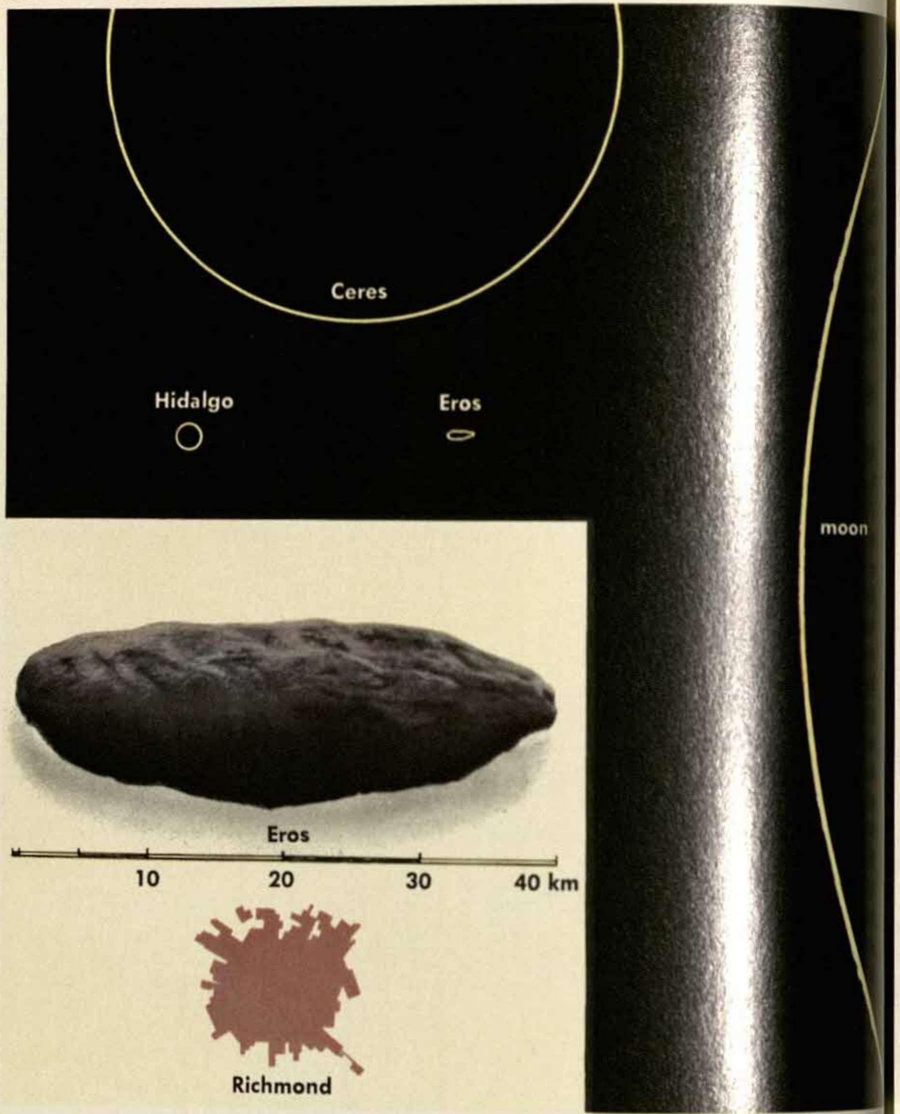
Soon after the new planet was named it passed behind the sun and could n longer be observed. Piazzi's observation were sufficient to confirm that the objec had been moving in an orbit correspond ing to 2.8 (or very close to it), but wer not sufficient, with the mathematica methods available, to calculate the exac shape of its orbit. There was the risk tha the new planet could no longer be ob served because of the impossibility o predicting its exact position. If too much time were allowed to pass, the difficulty of picking it up again would naturally increase. One of the greatest mathema-

2



ASTEROID ORBITS—Some asteroids have unusual orbits. The orbits of Eros (Illustration 1) and Hidalgo, for example, are on the average only a little farther from the sun than the Earth's. At its perihelion, Eros comes closer to the sun than Mars; Hidalgo travels much farther away from the sun than Saturn. Some asteroid orbits are strongly inclined to the plane of the terrestrial orbit; these orbits are also strongly elliptical. Since there are so many asteroids, every time one is observed, determination must be made as to whether it was previously observed and cataloged. The calculation of asteroid orbits is an international affair. Extensive work is presently being done in the United States, Germany, and the Soviet Union. Data are published under the auspices of the International Astronomical Union by the Soviet Institute for Theoretical Astronomy.

3a



b

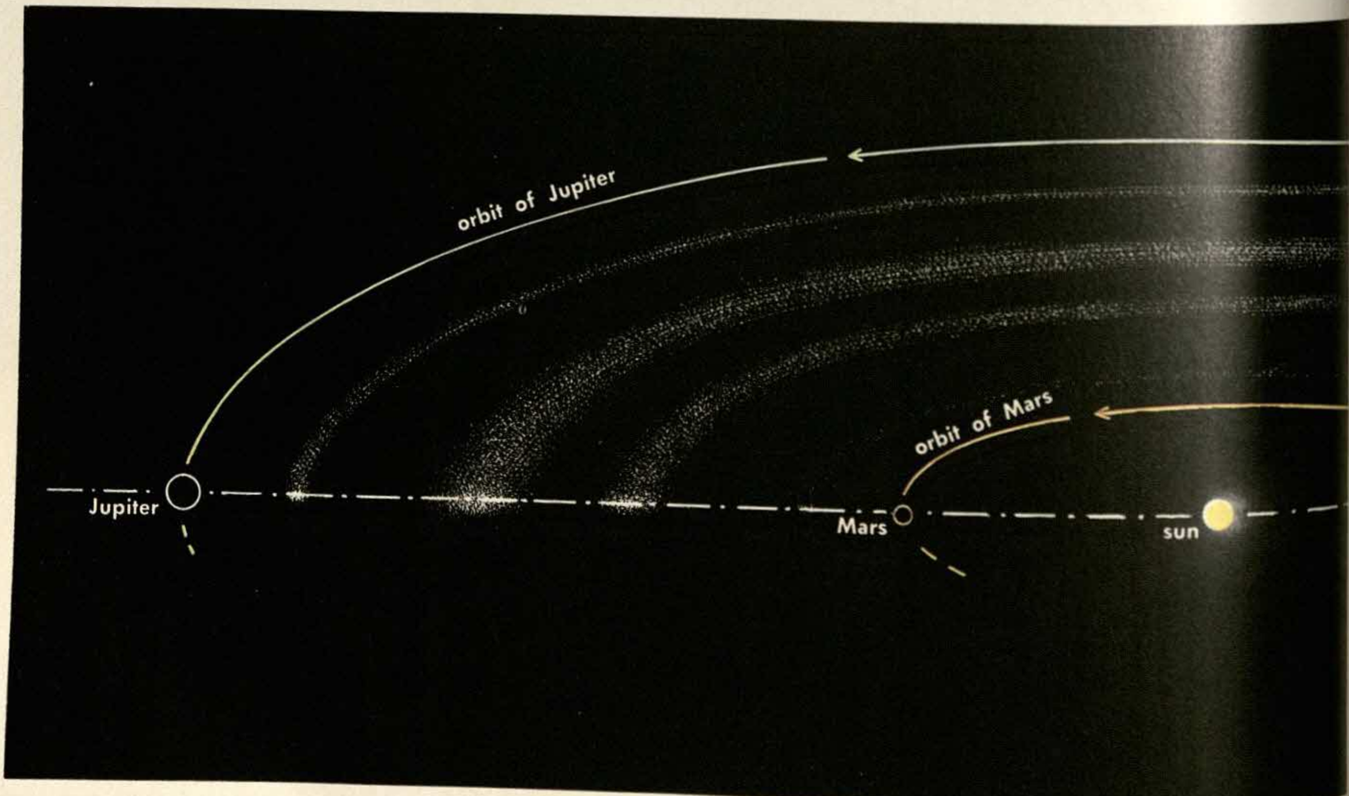
ASTEROID DIMENSIONS—Because of their small size and their distance from the Earth, the measurement of asteroids is difficult. Large asteroids can be measured directly, while measurement of the smaller ones is based on their luminosity. Among the larger asteroids, Ceres has a diameter of 77 km (about 48 mi); Pallas, 490 km (about 305 mi); Juno, 190 km (about 118 mi); and Vesta, 390 km (about 242 mi).

Most of the asteroids with recorded orbits, however, have diameters between 15 and 80 km (about 9 and 50 mi). Illustration 3a shows the relative proportions of some asteroids and the moon.

The larger asteroids, such as Ceres and Pallas, are almost spherical while the smaller ones are probably quite irregular in shape. Eros shows a great amount of variation in its light, indicating an irregular shape (Illustration 3b) and a rotation that presents alternately a wide and narrow surface to the Earth.

THE DISTANCES OF THE MINOR PLANETS BETWEEN JUPITER AND MARS—Most asteroids move in orbits close to that predicted for the unknown planet by Bode's Law. However, many travel in orbits that are larger or smaller than this. There also are zones between Jupiter and Mars where no asteroids are found. These zones, explained by Daniel Kirkwood in 1866, are known as Kirkwood's gaps. An asteroid in one of these gaps would revolve around the sun in a period equal to a half, a third, two-fifths, and similar proportions of the orbital period of Jupiter. Asteroids in these orbits would repeatedly be aligned in the same position relative to the sun and Jupiter; the disturbances caused in their orbits by Jupiter would accumulate until the asteroids were thrown into another orbit. Therefore, the asteroids between Mars and Jupiter are distributed, as shown in Illustration 4, in bands where their orbital periods are not proportional to the orbital period of Jupiter.

4



ticians of the age, Karl Friedrich Gauss, busied himself with the problem of working out and proposing a method whereby Piazzi's observations could be used to calculate Ceres' orbit. Gauss was successful, and his work became the basis for all subsequent preliminary orbit calculations.

SUBSEQUENT DISCOVERIES

Astronomers were satisfied that the missing planet had finally been discovered. In 1802 however, the German astronomer, Heinrich Olbers, discovered a second stellar body, subsequently named Pallas, which moved in an orbit quite close to that of Ceres. It was also apparent that Ceres and Pallas were not full-fledged planets but small planetary bodies, which were subsequently called asteroids, planetoids, or minor planets. Two more asteroids, Juno and Vesta, were discovered in 1804 and 1807, and then no others until Astraea was discovered in 1845. Since 1847 at least one new asteroid has been discovered each year. Some years are particularly favorable, and as many as 380 new asteroids have been discovered in one 12-month period.

HOW ASTEROIDS ARE DISCOVERED

Since photographic methods have been applied to the search, the number of asteroids discovered has increased considerably. The orbits of many asteroids intersect at a point on the ecliptic; therefore, if the zone immediately surrounding the ecliptic is photographed, asteroids are easily detectable. An exposure of several hours reveals the stars as luminous points; against this field, asteroids appear as luminous trails.

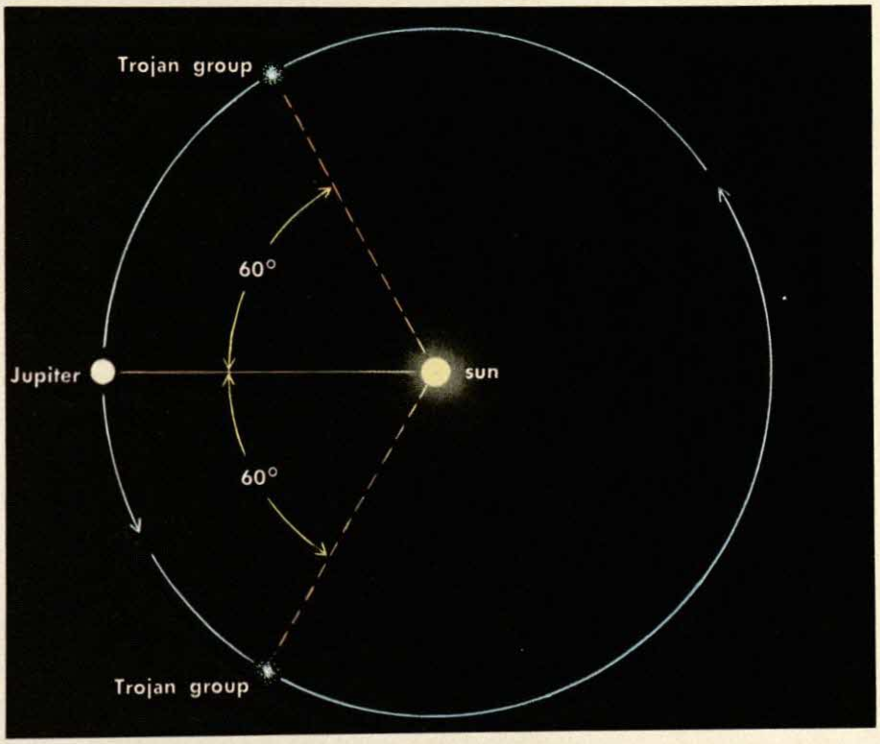
An efficient method of discovering the less luminous asteroids is to photograph the sky with an instrument moving at the same speed as asteroids. The asteroid then appears as a luminous disk, while the stars appear as streaks. In this manner, the maximum available light from the asteroid is registered on film.

NAMING THE ASTEROIDS

When the discovery of a new asteroid is announced, the asteroid is temporarily named with the year of discovery and with one or two letters indicating the order of the discovery. When it is established beyond doubt that the asteroid was not seen before, it is assigned a number; the discoverer then suggests a name. The first asteroid, for example, was called 1 Ceres. Generally, the names are feminine; the first asteroids were given the names of goddesses. Later, when the supply of goddesses from obscure mythologies was exhausted, new feminine names were devised. At present, the orbits of about 3,000 asteroids have been recorded. It has been calculated, however, that some 30,000 asteroids are within the range of a 2.5 m (100 in.) telescope.

When an asteroid's orbit displays exceptional characteristics (ellipticity or other irregularities), it is given a masculine name. In order to avoid mistaking a previously discovered asteroid for a newly discovered one, rigorous conditions have been set up that must be met before an asteroid is numbered.

5



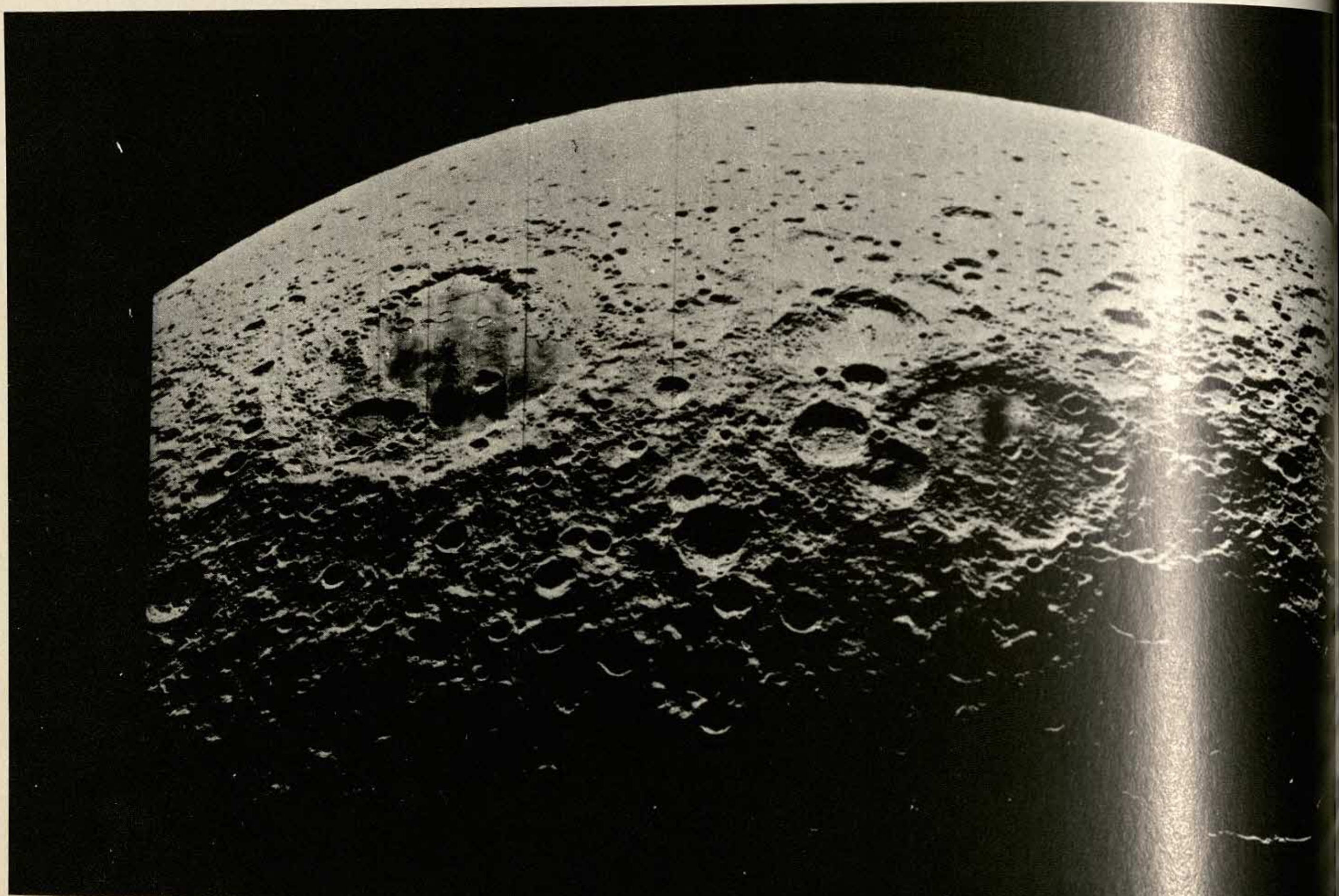
THE TROJAN GROUP—Three celestial bodies, joined by gravitational attraction, can move at points equivalent to the vertices of an equilateral triangle. Two groups of asteroids, called the Trojan asteroids, form equilateral triangles with the sun and Jupiter, moving in the orbit of Jupiter in the Lagrangian points (so-called after the French mathematician, J. L. Lagrange), who explained the stability of these orbits.

ORIGIN OF ASTEROIDS

The fact that most asteroids orbit in a rather small area suggests that the asteroids may have been formed by the explosion of a small planet. However, the circumstances that would cause a planet to explode have not yet been determined, and so this explanation of the evolution of asteroids is only a theory.

The asteroids seem to have originated as condensations in a tenuous part of the solar nebula between proto-Jupiter and proto-Mars. Gravitational instability could not occur in this ring. Therefore, no one large condensation formed a planet; instead, innumerable smaller condensations formed by accretion. The dimensions and composition of asteroids are in general accordance with predictions based on this theory. The composition and age of asteroids have been calculated from studying meteorites, which many authorities believe to be asteroid fragments that fall to Earth from outer space when asteroids collide.

LUNAR PHOTOGRAPHY | clues to the moon's geology



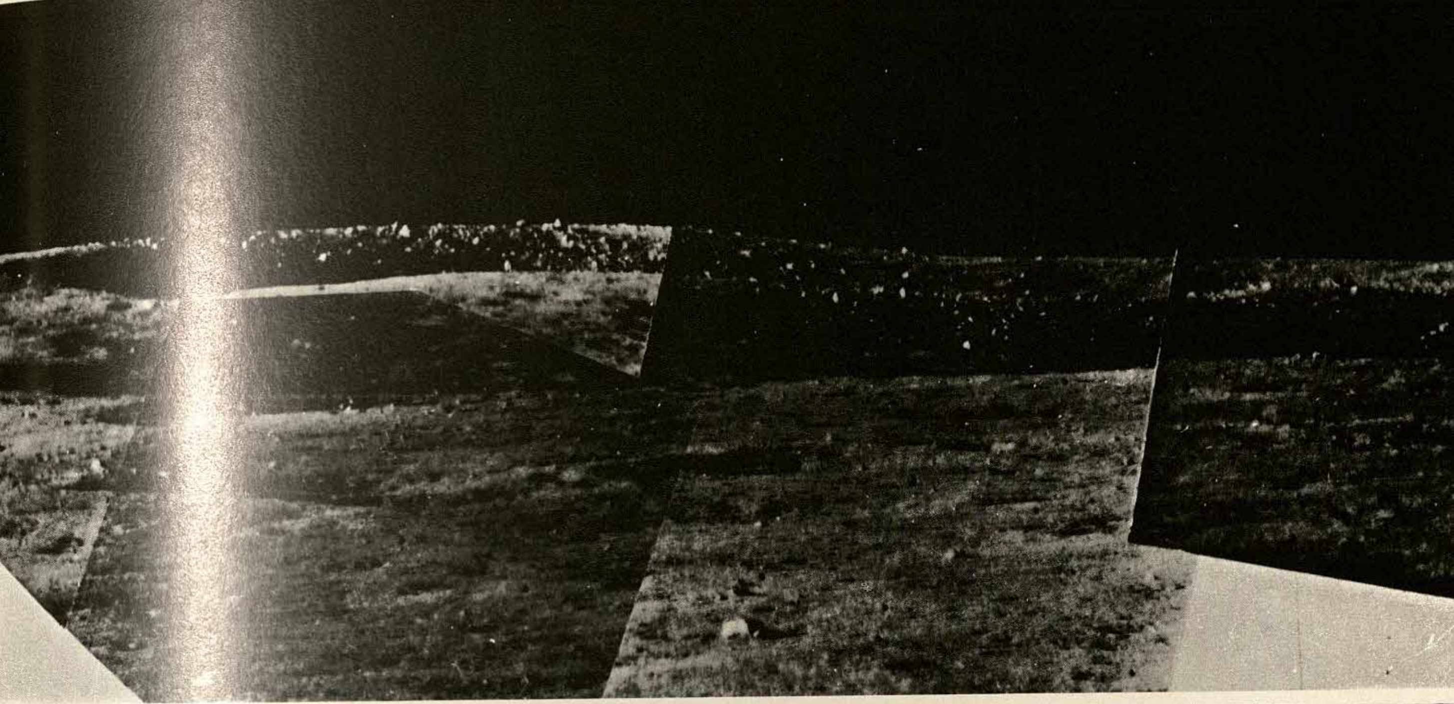
THE HIDDEN FACE OF THE MOON—One of the first lunar expeditions of unmanned spacecraft was the successful effort to observe the previously hidden face of the moon—the face that can never be seen from Earth because of the way in which the moon rotates on its axis. A Soviet spacecraft made the first trip behind the moon in 1959, but the pictures it transmitted were not of high enough quality to provide great detail, although they made possible the drawing of a preliminary map. The Lunar Orbiters launched by the United States in 1966 and 1967 transmitted more detailed information, including this photograph taken in 1967, showing the Sea of Moscow on the left. One fact revealed was the lack of large seas that characterize the side of the moon visible from Earth.

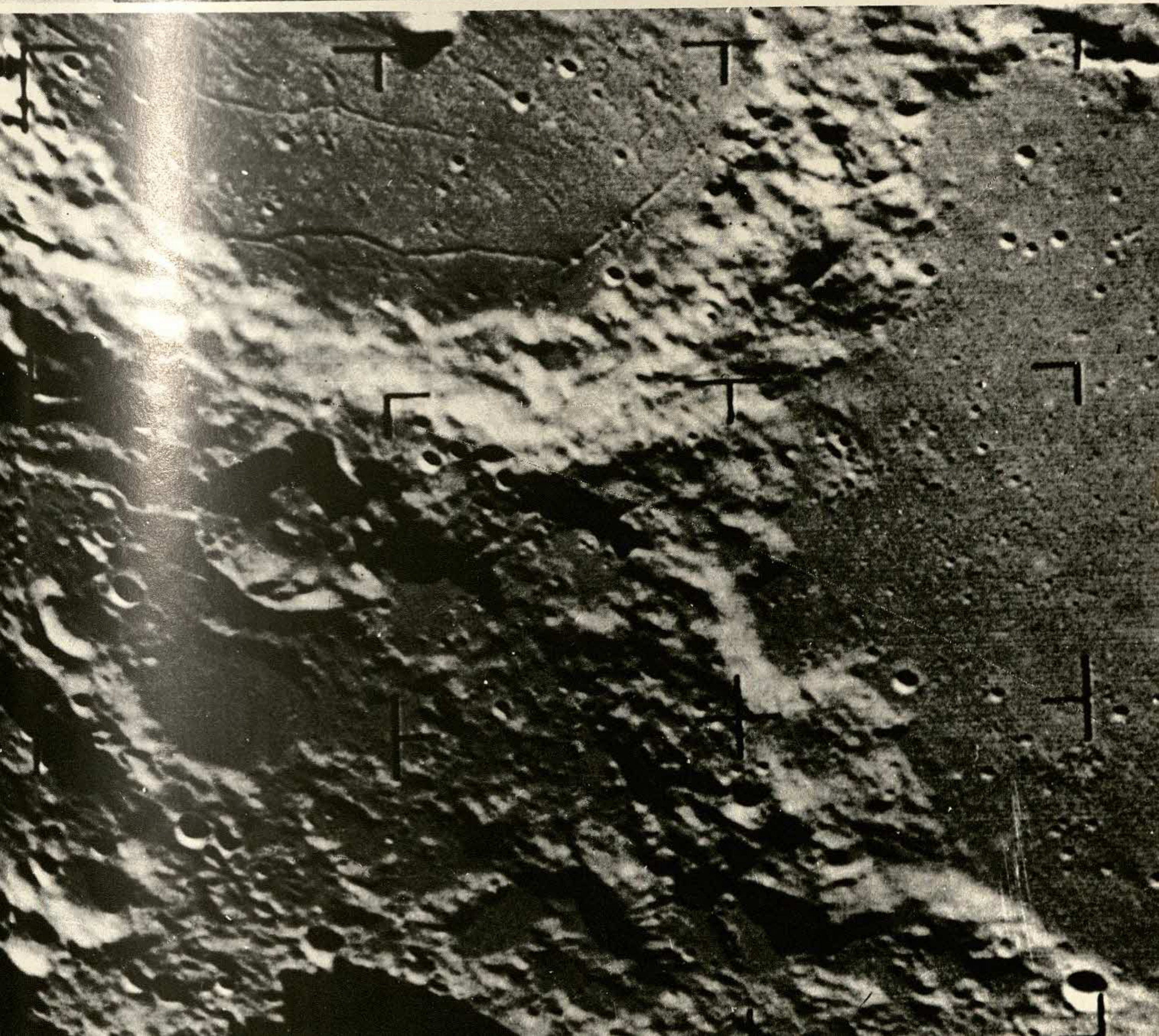
The advent of the space age has led to an entirely new aspect of lunar astronomy —the study of the moon as it appears in photographs taken by spacecraft near the moon. The first achievement in this field was the transmission to Earth of photographs of the far side of the moon by a Soviet spacecraft in 1959. These photographs, while of low resolution, gave astronomers their first look at the moon's far side. Most of the spacecraft photographs of the moon have come from the Ranger, Surveyor, and Lunar Orbiter missions carried out by the United States. These are now being complemented by photography from the Apollo command modules in orbit around the moon and by surface photographs made by the Apollo astronauts and by Soviet unmanned lunar surface devices.

The photographic missions of the Ranger, Surveyor, and Lunar Orbiter spacecraft were complementary. The Rangers used six television cameras to transmit pictures directly to Earth before a hard landing. The photographs gave a high-resolution view of a relatively small region of the lunar surface. Surveyor made a soft landing and then used a single television camera controlled from

THE LUNAR SURFACE—This photograph (Illustration 2), taken in November 1967 by Surveyor 6, shows the moon's surface. Astronomers, knowing that the moon has no atmosphere and that its surface has been constantly bombarded by meteorites, feared that the surface might be covered by a thick layer of loose dust into which the astronauts might sink. This and other photographs showed that such dust did not exist, and the evidence was confirmed when the first men landed on the moon. →

LUNAR CRATERS FROM RANGER 9—This photograph shows the craters east of the Sea of Clouds as they appear at an altitude of 1,246 km (about 774 mi). Rills and small craters appear clearly at this altitude. The last pictures transmitted by Ranger 9 just before impact had a resolution of 30 cm (about 1 ft). →

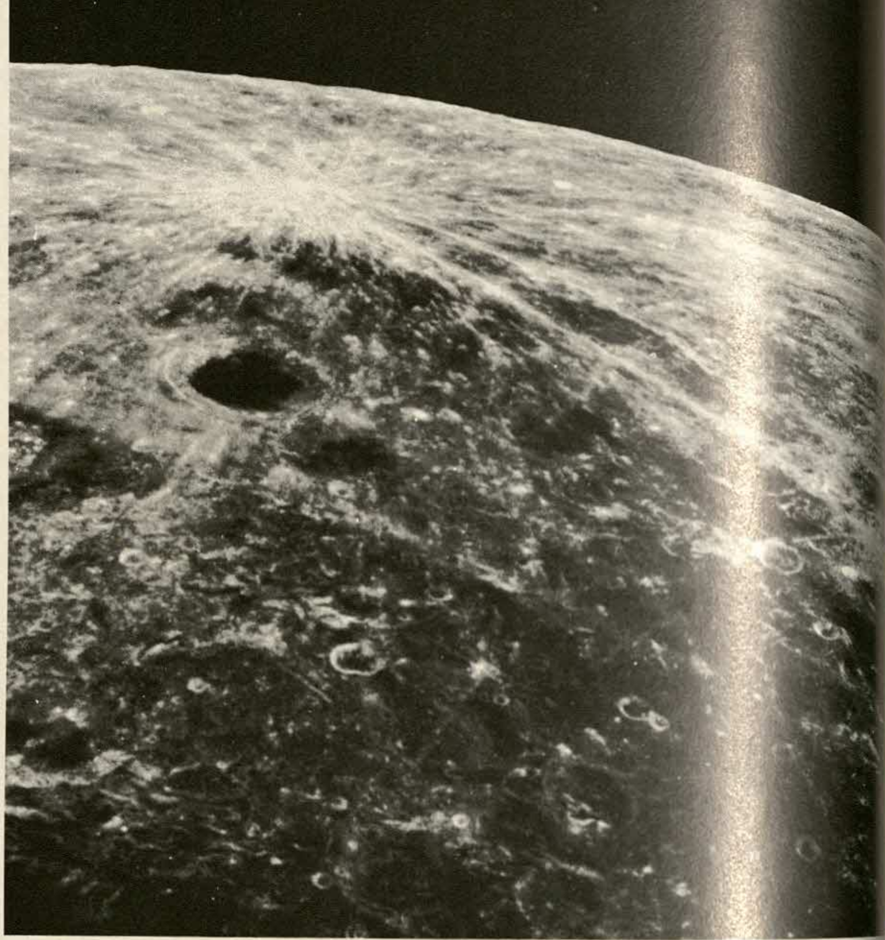





← **THE MOON FROM LUNAR ORBITER**— This photograph shows details in the Valley of Hyginus with resolution impossible from the Earth. These photographs have greatly added to astronomers' knowledge of the lunar surface.

EARTHQUAKE WATCH—One of the most interesting studies involves an investigation of the possibility of "earthquakes" on the lunar surface. The astronauts of Apollo 11 set up a seismograph there, and it has already registered light tremors—more evidence that the moon is not dead, and that some of its features may have originated in recent times. Some craters intersected with a network of rills are shown in this photograph; they are, in order of size, Goclenius, Magellan, Magellan A, and Columbus.

← **AN UNUSUAL FORMATION**—This Lunar Orbiter photograph has inspired a great deal of controversy. The principal feature is a sinuous rill that closely resembles a terrestrial river. Some scientists have suggested that this rill was at one time a river; others have suggested that it might have resulted from the escape of underground moisture millions of years ago. Still other scientists have proposed that the rill may be the trace of an ancient lava flow.

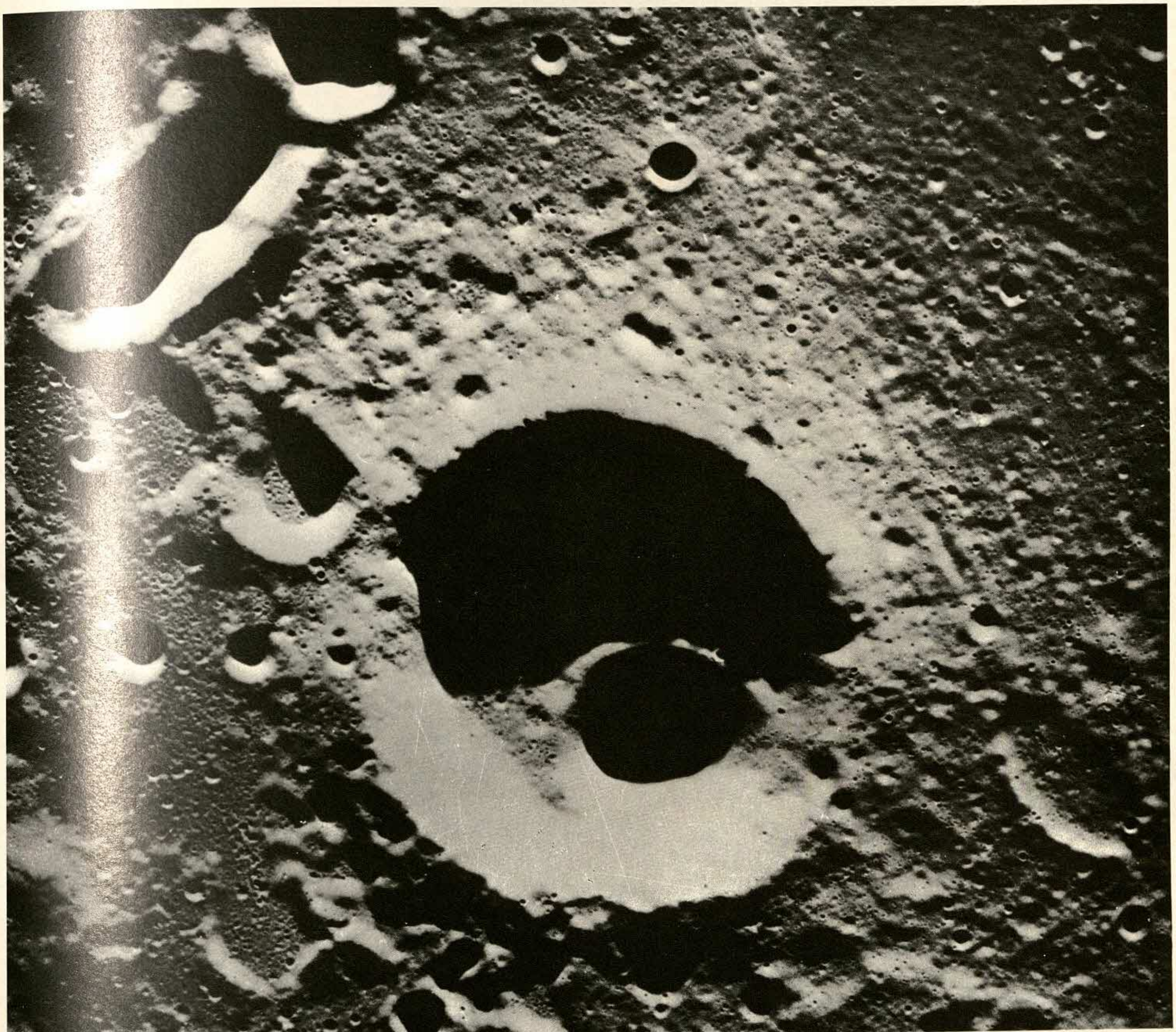


THE LUNAR SOIL—This photograph, taken from Apollo 8, shows one of the very bright, weblike formations that spread out from large and small craters on the moon. Neither the cause nor the composition of these formations is known, but the investigation of this problem, related to the minerals and rocks that compose the lunar surface, would lead to an interpretation of the physical history of the moon's mountains. There is probably no substantial difference between lunar and terrestrial rocks, but the composition of the magma and its metamorphosis are significant in a study of lunar geology (more accurately, selenology).

Earth to relay detailed pictures of the nearby lunar surface. The Lunar Orbiters contained two cameras that took photographs of large areas of the moon. These photographs were stored on film and later scanned and relayed to Earth. The original goal of the Lunar Orbiter program, to photograph potential Apollo landing sites, was so successfully carried out by Lunar Orbiters 1, 2, and 3 that Orbiters 4 and 5 were placed in orbits that allowed essentially complete mapping of the lunar surface.

These photographs are helping to answer age-old questions about the moon. Are the craters recent formations or ancient? Are they volcanic or the result of meteorite impacts? The spacecraft photographs indicate that each explanation so far offered contains some of the truth. The photographs are helping astronomers find the complete answer and are bringing closer the exciting possibility of constructing models for the large-scale geology of the moon.

The principal scientific objective of future manned lunar landings was to provide information on the age, chemistry, and mineral composition of the moon and to develop an understanding of the moon's structure. Seismometers were to be put where they could give a better understanding of moonquakes, and experiments were designed to study magnetic and gravity fields and heat flow characteristics of the lunar surface.



HIGH RESOLUTION PHOTOGRAPHY—The astronauts of Apollo 8 took these photographs (see left and above) from a low altitude above the lunar surface. The photographs are typical of the high resolution achieved by Apollo astronauts and their cameras.

EXPLORATION OF THE MOON

"zooming in" on the Earth's only satellite

Apollo 11 astronaut Neil Armstrong's "giant leap for mankind" onto the surface of the moon dramatically signaled the beginning of a new era in space exploration. It was also the culmination of a decade of intense scientific interest and study—at ever closer ranges—of the Earth's only satellite.

Man's curiosity about his nearest celestial neighbor is as old as man himself. Telescopic study over the past few centuries led to accurate knowledge of many lunar characteristics, such as the moon's motion around the Earth. However, regarding the question of the composition and origin of the mountainous forms on the lunar surface, few astronomers were prepared to even offer a hypothesis—and when they did so, there was no possibility of proving it. This situation changed dramatically when man learned to travel in space.

The Apollo 11 mission was preceded by many preparatory steps following a master plan of extremely precise experiments and explorations by both unmanned and manned spacecraft. Each of these, in addition to proving the capabilities of the complex equipment needed to put a man on the moon, also added to scientific understanding of the satellite. Armstrong's step was the thrilling climax, but events leading up to it were almost as exciting,

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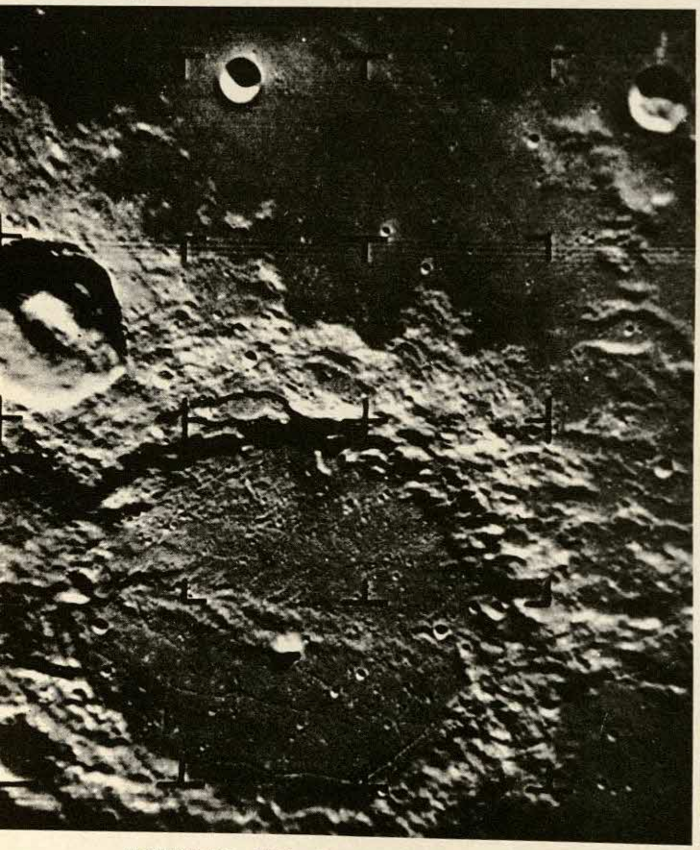

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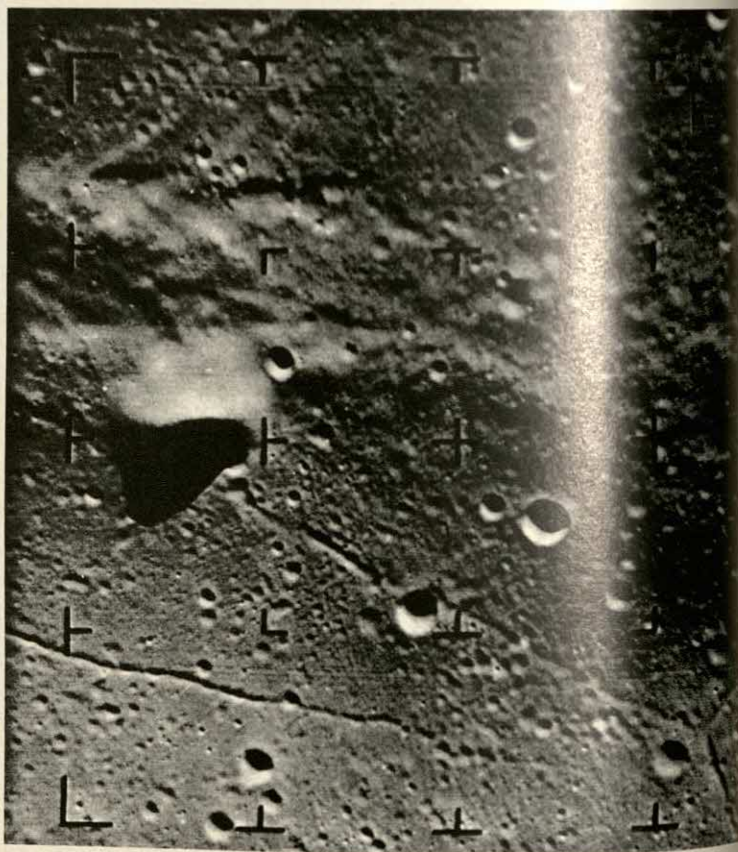

ALPHONSUS AND ITS LITTLE PEAK—This photograph (Illustration 1a) of the crater Alphonsus was taken by Ranger IX on March 24, 1965, from a height of 415 km (about 257 mi). While the telecameras used in the Ranger program did not produce results as satisfactory as might be obtained with more recent equipment, the definition and detail are vastly superior to pictures taken through Earth-bound telescopes, and the photographs played an important role in the making of accurate moon maps.

Detail is greatly increased in this second photograph (Illustration 1b) taken by the same Ranger IX a few instants later during its descent, at a height of 93 km (about 58 mi). The small craters on the lunar surface are much more clearly seen. A photograph transmitted from a still closer distance during this mission picked up details as small as a man's hand.

in a scientific and technological sense.

The first step was to make a precise photographic map of the moon, using the best available instrument for obtaining the images. The Observatory at Pic du Midi in the French Pyrenees was chosen for the task. A refracting telescope, with a 60 cm (about 24 in.) objective lens was used.

From the photographic map, a cartographic map was made. This was a difficult undertaking because of the lack of stereoscopic effect in the photographs and the absence of a "sea level" that could be used as a reference point, as in maps of the Earth. Objectives for lunar missions were determined from this map.

In 1959, an unmanned Russian spacecraft completed a circuit of the moon and sent televised pictures of its hitherto unseen back face. Man had finally realized the ancient philosophers' dream of seeing the other face of the moon. While the pictures were not very detailed, it was possible to construct the first rough map —comparable in detail to those traced by Galileo with his first telescope in 1608.

OBJECTIVE: MOON LANDING

By 1960, plans were completed for the program that would result in the landing of astronauts on the lunar surface. Comprehensive unmanned programs were undertaken to prepare for the manned effort. One urgent question that had to be answered was the nature of the lunar soil, to which Earth-based studies provided no clues.

Under the Ranger program, spacecraft were sent to various points on the moon; these spacecraft transmitted increasingly detailed pictures back to Earth before crashing into the lunar soil. The Surveyor program involved landing unmanned satellites on the moon's surface to test the hardness and elasticity of the soil and to photograph the surrounding terrain to determine how uneven it actually was. Finally, the Lunar Orbiter program put telecameras into orbit around the moon to obtain precisely detailed closeup photographs of its surface, so that maps as perfect as possible could be constructed.

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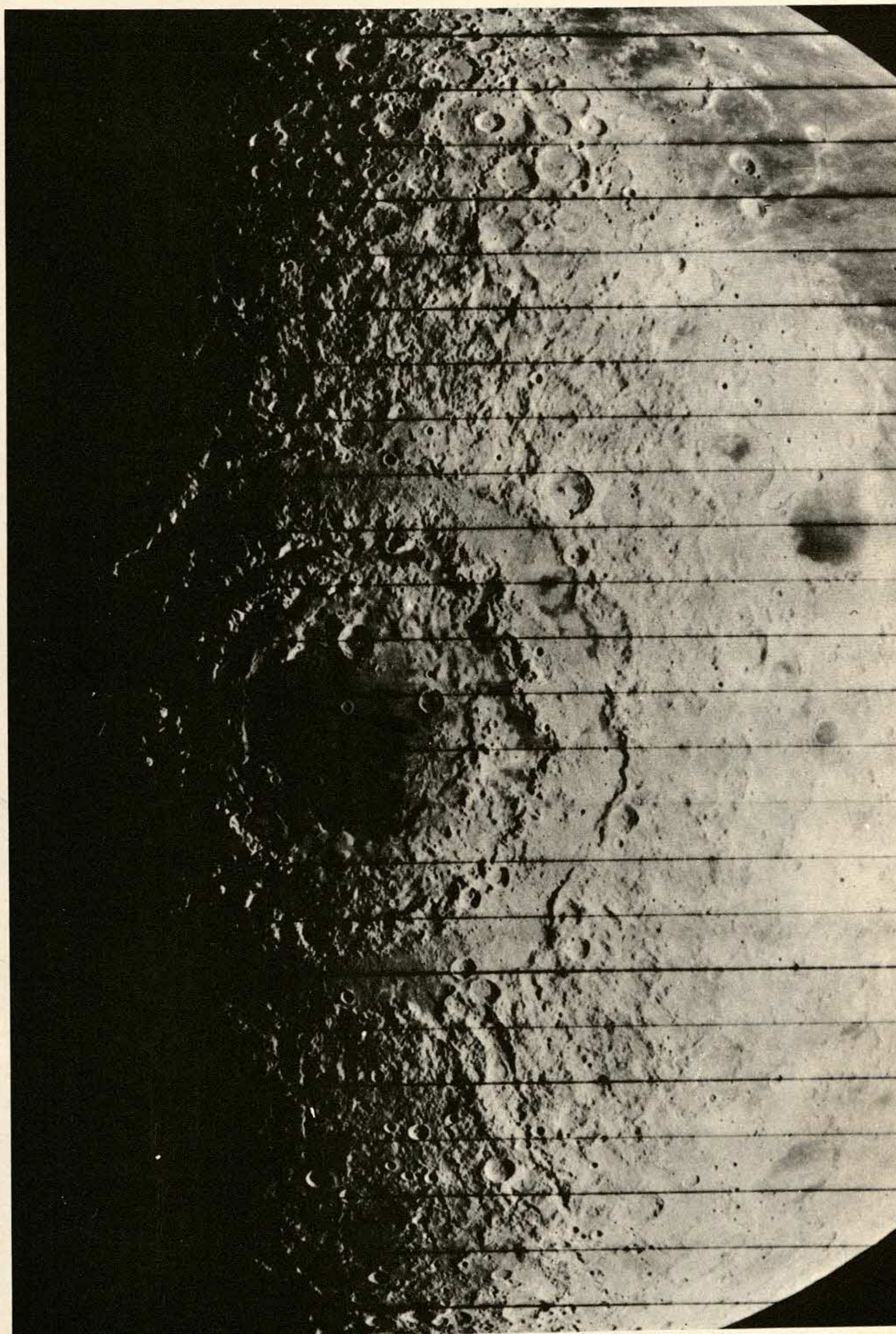

THE EASTERN SEA—This photograph, taken by Lunar Orbiter IV at a distance of about 3,140 km (about 1,950 mi) from the moon, shows the Eastern Sea, which is barely perceptible from Earth. The Eastern Sea is near the Ocean of Storms (to the left in the photo).

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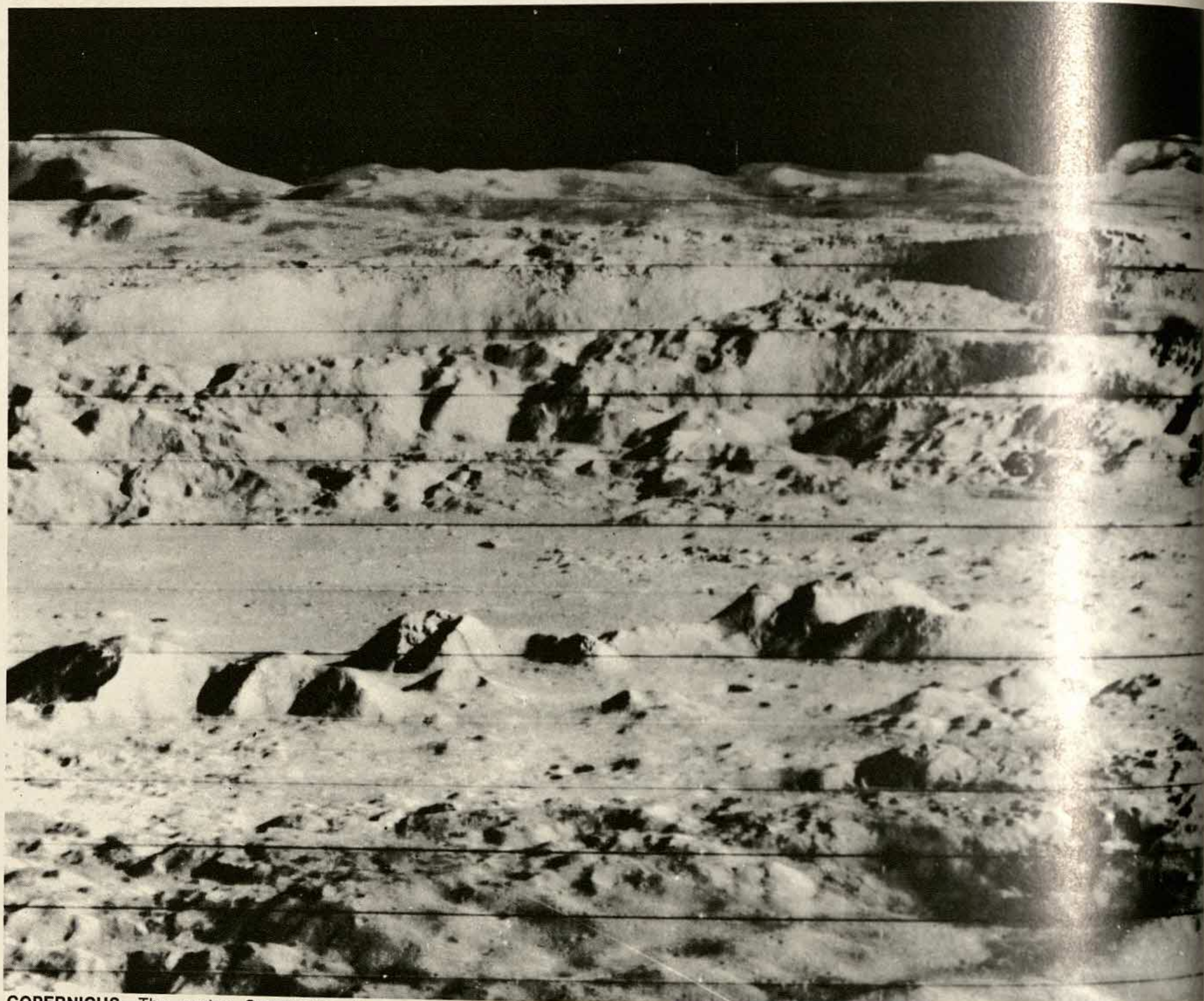

COPERNICUS—The crater Copernicus rises from the vast plains in the eastern part of the moon. In this photograph, the crater is seen from an elevated perspective. The Carpathian mountains and the Gay-Lussac promontory are in the background.

Careful interpretation and analysis of the results of these three programs suggested the most likely landing sites for man.

Late in 1968, Apollo 8 became the first manned craft to orbit the moon, paving the way for the lunar landing of Apollo 11 in July, 1969. Astronauts Armstrong and Aldrin collected samples of moon soil and rocks and set up instruments for scientific observations: a seismometer, a solar particle collector, and a mirrorlike laser reflector designed to permit very accurate measurements of the Earth-moon distances.

The Apollo 12 mission was planned for more detailed geological exploration of the lunar surface. Astronauts Conrad and Bean set up another seismometer and solar particle collector, along with a spectrometer to measure solar wind, a magnetometer (which recorded a faint magnetic field on the moon), an ionosphere and lunar atmosphere detector, and a lunar dust detector. These devices were all powered by a nuclear generator to keep them transmitting data to Earth for at least a year. The astronauts also collected more samples of moon soil and rocks, and brought back pieces of a Surveyor spacecraft that had landed on the moon some two and a half years earlier.

After leaving the moon and rejoining the command module, the astronauts jettisoned the lunar module, intentionally crashing it onto the lunar surface. The impact set up vibrations lasting almost 55 minutes, astonishing the scientists on Earth who were reading the seismometer.

This phenomenon and the rocks and soil brought back from the moon by the Apollo astronauts are being carefully studied and analyzed by scientists.

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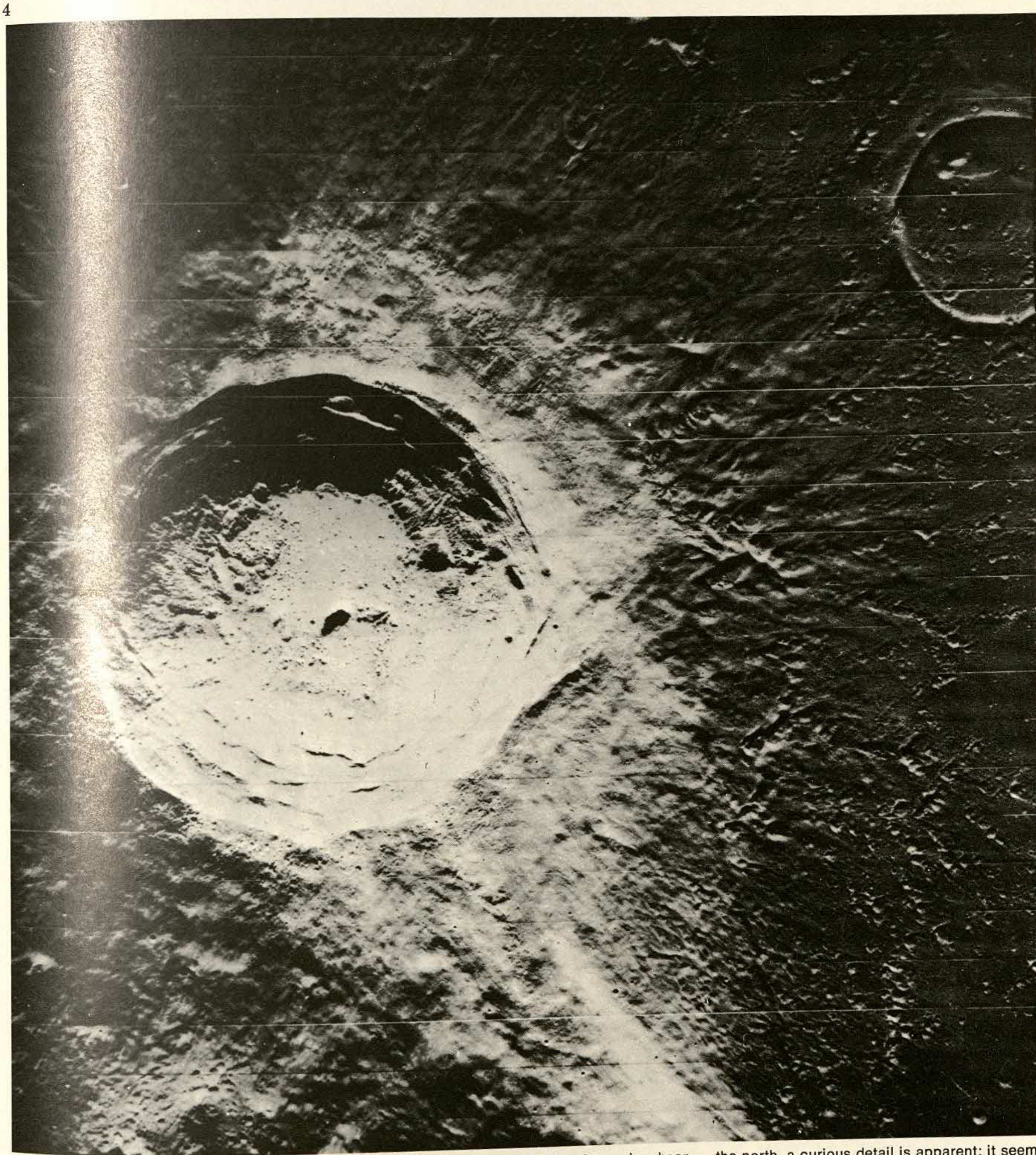

ARISTARCHUS—This photograph of Aristarchus was taken by Lunar Orbiter IV. The exceptional detail shows unusual structures that were previously detected in telescopic observations from Earth, pointing up the outstanding luminosity of this section of lunar soil. Toward the north, a curious detail is apparent; it seems as if a strong wind had deformed the surface of the crater.

5

TYCHO—The altitude of the Lunar Orbiter spacecraft varied considerably. Photographs taken at greater distances showed details of larger features of the lunar surface, such as the crater Tycho. For obvious reasons, such an area is not an ideal lunar landing spot.

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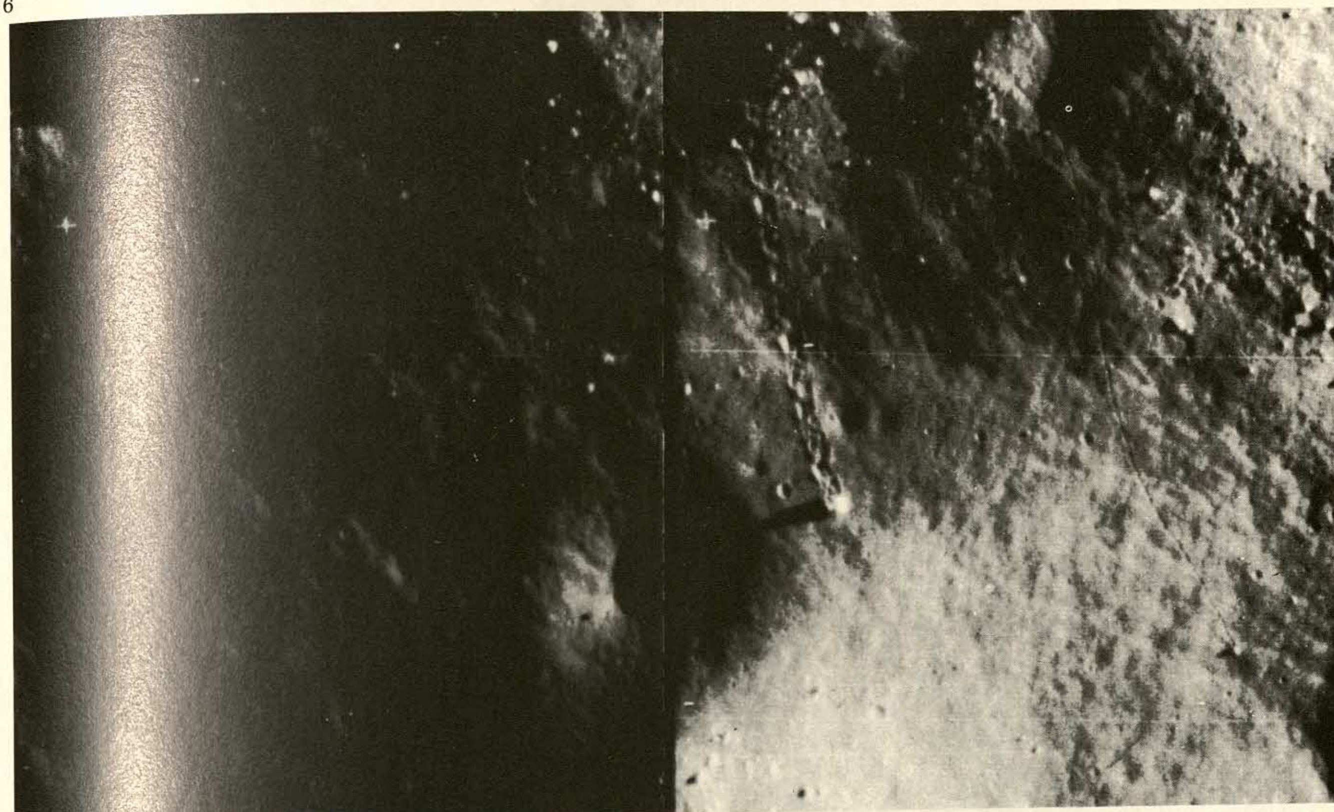


THE MOST MINUTE DETAILS — This photograph was taken with a powerful telephoto lens from a height of about 160 km (about 100 mi). In the small crater Vitellus, located in the Mare Humorum (Sea of Moisture), two rocks that have rolled down the inner slope are clearly visible. The larger has a diameter of about 22 m (about 72 ft); the smaller about 5 m (about 16 ft). The larger has left a trail about 270 m (about 880 ft) long; the smaller about 360 m (about 1,180 ft). The fairly smooth soil clearly shows up the presence of tiny craters, no more than a few meters in size. Greatly enlarged, this photograph illustrates the tremendous amount of detailed information that was gathered before man first attempted to set foot on the moon.

KEPLER—This is how the crater Kepler appeared to Lunar Orbiter III from an altitude of 50 km (about 30 mi). Distant mountains and the pronounced curvature of the lunar horizon are clearly visible. Countless tiny craters mark even the smoothest lunar seas. More detailed photographs show that the lesser craters are as small as a few meters in diameter.

7

OBSERVATION OF THE MOON'S SURFACE | techniques and instruments

The full moon rising large and red on a warm summer's night may seem more the stuff of dreams than of astronomers. A little later, however, when the moon has risen fully above the horizon and appears whiter and more luminous against the night sky, the various formations on its surface can be seen. These forms suggest many different things to different people: some see a face; others imagine various animal forms. If the moon is viewed through a pair of binoculars, these forms appear more distinct. Some of them are darker and others lighter than what may be called the normal color of the moon's surface. Nearly all the dark patches have a rounded shape, while the light patches are more irregular. Binoculars are not powerful enough to bring out more details. However, if the moon is observed through an astronomical telescope over a period of a week—for example, from the third day of the new moon to the tenth day—the surface will spring into relief and the mountains, valleys, plains, and tablelands can be distinguished. Although at first there will be a temptation to compare these features to similar features on Earth, it soon becomes obvious that only a slight resemblance exists between the two.

OBSERVATION OF THE MOON

The distance between the moon and the Earth is about 384,000 km (about 239,000 mi), making it the closest of all the celestial bodies. It is close enough for the distance to be considered in terms of distances on Earth. If one were to go around the Earth 10 times, the distance covered would be a little more than the distance between the Earth and the moon. Because it is so close, the moon's landscape can be seen clearly with a telescope.

Between the Earth and the moon there is little but empty space. The moon has no atmosphere, and is not surrounded by clouds as the Earth is. Therefore, when the Earth's atmosphere is cloud-free the moon's features can be seen clearly. If a telescope with a magnifying power of 60 is used, the moon appears the size of a disk 13 cm (about 5 in.) in diameter seen at a distance of 25 cm (about 10 in.). With a telescope that has a magnification of 300, the moon appears the size of a disk 75 cm (about 30 in.) in diameter seen from a distance of 25 cm.

Galileo was the first man to draw a map of the moon. His telescope enabled him to see features six times more clearly than with the naked eye. Knowledge of the moon's surface has increased greatly since then, and now it is possible to map the smallest features of the lunar landscape, even those measuring only a few hundred yards. Today, the best and clearest means of examining the moon's relief is by photographs.

No photograph, however clear, is as distinct as the direct image seen through the telescope used in taking the photograph. To be more precise, a telescope can distinguish three times the detail that can be photographed. For example, a reflecting telescope with a mirror 60 cm (about 24 in.) in diameter is needed to photograph details that can be seen through a telescope only 20 cm (about 9 in.) in diameter. However, if the diameter of the telescope is increased to more than 50 cm (about 20 in.), the turbulence of the Earth's atmosphere will diminish the clearness of details in proportion to the increased power of the instrument. Therefore, a telescope with a mirror of 30 cm (about 12 in.) is the ideal instrument for lunar observation.

Man's lunar landings have produced televised pictures of the moon with such clear, detailed precision that they show

THE RISING MOON—As it rises above the horizon, the moon gradually loses the elliptical form caused by atmospheric refraction and gradually changes to a circular appearance.

1

features that could never have been taken by "unmanned" photographic methods.

HOW TO OBSERVE THE MOON

If the moon is viewed on the horizon, it seems much larger than when it is high in the sky. This is an optical illusion. If any object is observed on, or just above, the horizon it will seem much larger than it actually is. For example, a ship far off on the horizon will appear much larger than the same ship placed on top of a mountain at the same distance. Another point to bear in mind is that any object which has small contrasting details will appear larger. The rigging of a sailing ship makes it seem larger than it really is, and the patches on the moon have the same effect of increasing its apparent size.

It is also easy to overestimate heights of mountains. To carry out an experiment on this illusion, make an estimate of the angle made by a mountain with the horizon. Then lie flat on the ground and look up at the peak, at the same time keeping the horizon in the field of vision. This can be done because the human eye has a vertical angle of vision of 105°. It will be noticed that the mountain that previously seemed to loom large now appears smaller.

The same illusion is true for the constellations—they seem larger when the Earth's rotation brings them closer to the horizon. However, even though the moon on the horizon appears larger than it does when it is at its zenith, its image is actually reduced in size by a process of refraction. What happens is that both its upper and lower edges are raised above the horizon by atmospheric refraction, but the lower edge is affected a little more than the upper. Hence, the moon assumes an elliptical shape with the smaller axis vertical. The photographs in this article make this plain. They were taken as the moon appeared over the horizon and rose about 10°. It can be seen that as the moon rises, its shape changes gradually from elliptical to circular with the same diameter as the larger axis of the ellipse (Illustration 1).

It might seem that the best position at which to observe the moon, or any other celestial body, would be when it is low on the horizon, but such is not the case. This is because the moon's light must pass through more air when it travels horizontally, and so is disturbed by the comparative thickness of the air and by the turbulence in the lower layers of the Earth's atmosphere.

THE BEST CONDITIONS FOR OBSERVING THE MOON

An observation of the moon will show clearly the differences in the brightness and color of its soil and, above all, the shapes of its features. The best way to see these features is to take advantage of the clear shadows they throw when they are lighted by the sun. These shadows are

2

THE TERMINATOR—Along the terminator, the border between light and dark, the moon's features are particularly clear. Away from the terminator, the moon appears featureless.

especially long when the sun is low on the lunar horizon. During a lunation (the name astronomers give to the lunar month) the height of the sun on the lunar horizon varies, so the illumination of the landscape is constantly changing. Some general rules may help in understanding the way shadows fall on the moon. The shadows cast on the surface of the waxing moon fall in the opposite direction to those cast on the waning moon. During full moon and the days immediately preceding and following it, sun, Earth, and moon are in a direct line in that order. The moon and the sun are opposite each other with the Earth in the middle, and the sun's rays strike the moon directly (Illustration 4). In this period shadows cannot be seen because they are hidden by the surface features themselves.

This is why the moon's surface appears flat and featureless when it is full. Only bright and dark spots—due to the different composition of the moon's soil—can be seen. This is why this phase of the moon does not offer the best conditions for observation. The features are best observed by following the edge of the sun's circle of illumination as it progresses over the surface of the moon during the lunar month. This border between light and dark, corresponding to the points of the lunar surface from which the sun would be visible on the horizon, is called the terminator. Along this line, the moon's surface falls into relief, as can be seen clearly in Illustration 2. Away from the terminator, the surface appears flat and featureless.

EARTHSHINE

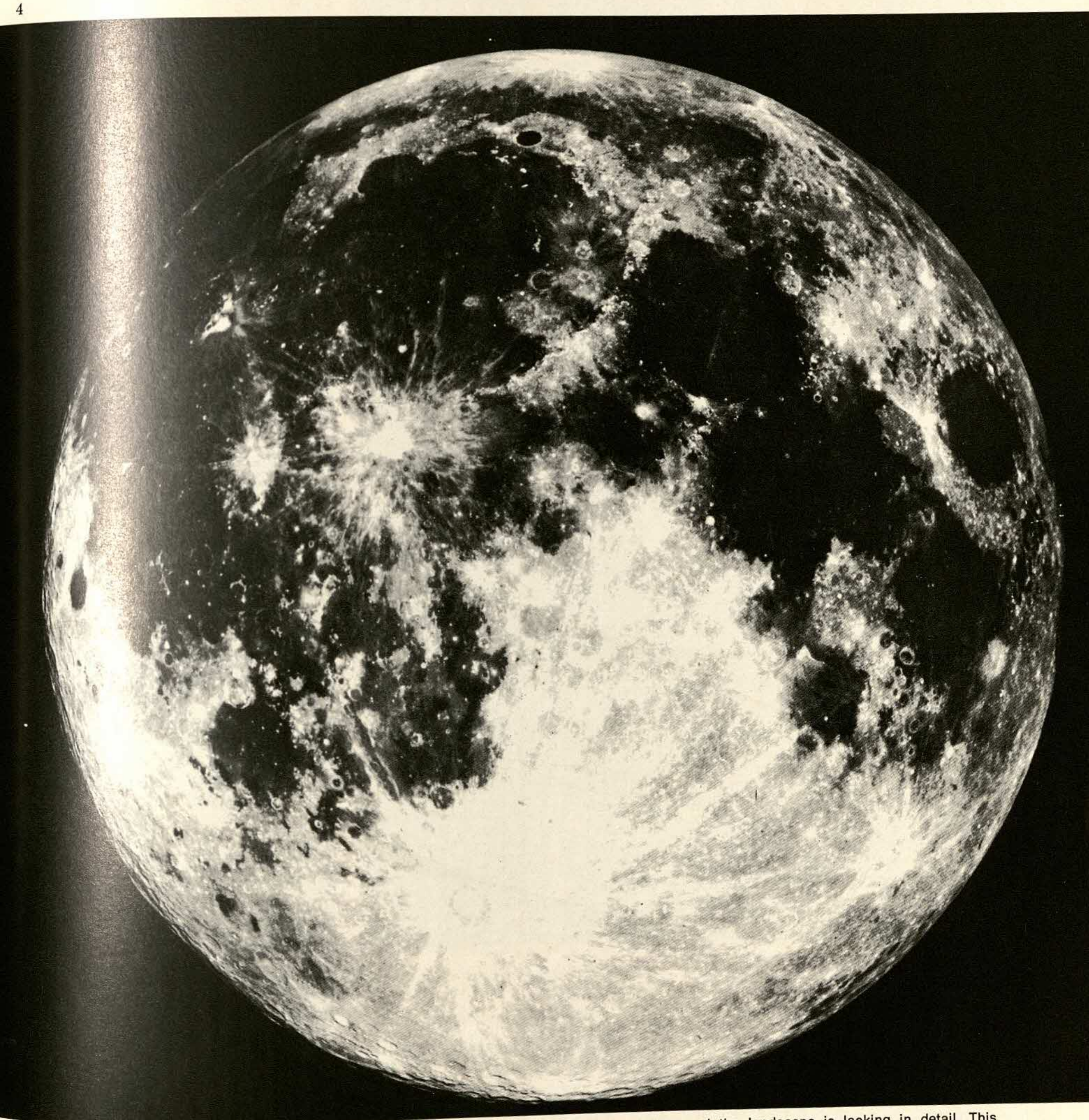
When the moon is almost new, sun, moon, and Earth are in a direct line in that order. From the moon, the Earth looks rather like the full moon lighted by the sun's rays. However, because the Earth is larger than the moon, it reflects more light than the full moon. The surface of the Earth visible from the moon is about 13 times greater than the surface of the moon visible from the Earth. Also, the surface of the Earth has a much greater reflecting power than the surface of the moon because the Earth is covered with clouds, deserts, and seas. These combined effects cause the Earth to emit a light 50 times brighter than that of the full moon. This light cast by the Earth, although far weaker than the sun's, is sufficient to illuminate the surface of the moon, making it visible under favorable circumstances. This light, earthshine, is sometimes called the ashen light because of the grayish tinge it gives to the part of the moon it illuminates (Illustration 3a, 3b, and 3c).

3a

3b

EARTHSHINE—Earthshine is shown as it appears on the third day of the lunar month (Illustration 3a); as it is seen on the fifth day of the lunar month (Illustration 3b); and as it is seen on the ninth day of the lunar month (Illustration 3c).

3c



THE FULL MOON—Under these circumstances it is not possible to observe the shadows thrown by the features on the lunar surface because the sun's rays illuminate it directly and the landscape is lacking in detail. This phase is poor for lunar observation.

THE MOON'S SURFACE | the geology of the Earth's only natural satellite

When looking at the craters of the moon, it is natural to ask how they were formed, because their shape is similar to that of volcanic formations on Earth, or of the few known meteorite craters.

These formations are not the only surface features (even if they are in the majority), and the other forms which can be seen with a telescope are no less interesting.

LUNAR MOUNTAIN CHAINS

Mountain chains on the moon have a different structure from those on Earth. Observation of their general shape is enough to show up these differences. The lunar Apennine chain is one example: it is a succession of rather pointed peaks, spaced irregularly but rather close together. Toward the Mare Imbrium, the Apennine chain becomes sheer and the highest peaks rise up almost vertically from this sea. Some peaks tower as much as 8,800 m (about 28,900 ft) over the plain below.

COPERNICUS—This crater has a diameter of 90 km (about 56 mi) and is one of the best formed and most regular of all those found on the lunar surface.

ARISTARCHUS — This crater is covered by light-colored dust, so it shows up as a white patch, even if it is only lighted by earthshine.

On the opposite side, however, the peaks decline progressively in height down to the plain of the Mare Vaporum.

Between one peak and another are steep depressions. The shape of these depressions is different from that of long valleys on Earth, and the depressions are

TYCHO—The crater is surrounded by a strip, almost a halo. From this, rays spread out as far as the dark side of the moon. Tycho is located in the southern highlands.

not comparable to the saddle types that separate one peak from another in a typical terrestrial mountain chain. The shape of valleys and saddles on Earth is determined by erosion from water and ice. A valley on Earth has an elongated shape and its walls have a characteristic slope caused by the way water passes through the mountains to open up a path to the sea. Saddles are low areas along ridges; they may connect valleys on opposite sides of the ridge line. On Earth, these valleys are always formed either by water erosion or by the action of glaciers. The shapes that are so characteristic of Earth formations do not occur at all on the lunar Apennines of the moon. The other large mountain chains on the moon are similar in shape to the Apennines.

THE FORMATION OF LUNAR MOUNTAIN CHAINS

On Earth, mountain chains have been formed either by the movement of continental masses that were raised or low-

ered because of horizontal pressure, or through the re-establishment of isostatic equilibrium disturbed by substantial rises of magma. On the moon, the large mountain chains probably were formed by the upthrust of material caused by the impact of meteorites and asteroids. The surface relief of the Earth and the moon are different, however, mainly because the Earth's surface has been altered by erosion from water and ice. This erosion did not occur on the moon, and the formations that are seen today are similar to what they were when they were formed in remote times, probably more than a billion years ago.

EROSION OF THE LUNAR SURFACE

Erosion processes do take place on the moon, even if the forces that cause them are much less powerful than the force of water. The three types of erosion processes are:

1. The invasion of fluid lava. This type of erosion is responsible for most of the destructive activity in the past. The Sinus Iridum is a clear example of this. Once it was a complete circle; now it is reduced to a single arc opposite the side eroded by the lava.
2. Change of temperature. Every time the sun rises over a point on the moon's surface, the temperature soars from many degrees below 0° C to as high as 120° C. This gain in temperature (and the corresponding loss when the sun goes down) results in a strong expansion and contraction of the rocks, which causes them to split. Over a long period of time, this type of erosion gradually flattens the surface relief.
3. The impact of micrometeorites. Large meteorites are rare, but those with a mass of less than 1 g (about 0.03 oz) are quite common. A meteorite of 1 g at a velocity of 40 km/sec (about 25 mi/sec) has the energy of a heavy machine-gun bullet, so that when it strikes a rock, even a hard one, it produces a small crater nearly a foot deep and at least twice as wide.

On the Earth, water takes eroded matter away and then deposits it in a valley or in the sea, thus making surface features gradually disappear. On the moon, however, the eroded matter accumulates near the point it came from, so that in time it protects the terrain it covers.

LUNAR ROCK SAMPLES

In man's first visit to the moon in 1969, about 50 pounds of rock and dust were collected and brought back to Earth from the Sea of Tranquility, one of the moon's flattest areas. In addition to many craters, the ground near the spacecraft was covered with loose, broken stones overlying solid rock that was porous and weakly coherent. All the craters visited by the astronauts appeared to have been caused by meteorites striking the moon, and the loose rock on the surface consisted of impact debris. The rock samples collected include basaltic igneous rocks, lunar soil, and microbreccias. The chemical composition of the lunar igneous rocks is generally similar to basalts found on Earth, but they are richer in titanium. The viscosity of the lunar lavas is about one-tenth that of Earth basalt; so it is possible that the lunar lava flows spread far across the moon's surface into thin sheets.

ALPHONSUS AND ITS ACTIVE VOLCANO

Since about 1945, many studies on the light effects of the lunar surface have been made. In particular, attempts have been made to reproduce the roughness of the dust deposits in the laboratory. Presumably, thermal erosion and meteorite bombardment produced this dust, which was then deposited on the lunar surface. The dust is easily identified, as it polarizes the light given out by the satellite; in fact, the light coming from many parts of the lunar surface is polarized. Studies have also been made of the color of the moon's surface, or at least of the shades of color superimposed on the normal grayness of the moon.

Finally, attempts have been made to discover and measure the fluorescence, if any, of lunar rocks. For this, extremely accurate spectroscopic studies of the surface of the moon were needed. On November 3, 1958, a cloud seemed to rise from the central cone of the crater of Alphonsus. Several astronomers aligned their spectroscopes immediately on the point where the gases were being emitted and registered the spectrum of the light coming from that part of the moon. Most of this light obviously originated from the sun and was reflected by the rocks; but superimposed on this familiar spectrum was a clear luminescence corresponding to the central peak, presumably caused by an emission of hot gases. The gases emitted by volcanoes on Earth are luminous because they react with the oxygen in the atmosphere (if they did not, they would be difficult to see in daylight). However, oxygen and other gases that the volcanic vapors could react with are absent on the moon, so the only source of luminescence could be the spontaneous decomposition of molecules no longer subject to underground pressure, or luminescence caused by the disturbance of solar radiation. This luminosity has been observed spectroscopically; its existence confirms that activity is still taking place on the moon.

Other interesting observations that confirm the existence of active zones are those aimed at the discovery of points on the lunar surface that are hotter than others. It has been observed that there are zones that do not cool as rapidly as the rest of the terrain when the sun sets. When the craters of Tycho, Copernicus, and Aristarchus are no longer lighted by the sun, they stay warmer than the surrounding terrain for almost the entire lunar night. In fact, their temperature varies between 40° and 60° C (104° and 140° F). This is possible only if the craters are kept warm by another source of heat. A possible explanation of this abnormal heat, following the analogy of the sea, which stores more heat than the Earth and so retains it during the night and also during the winter months, is that these rocks have a similar property of heating and cooling more slowly than others. If this were true, these rocks should be cooler than the surrounding area during the lunar day, but they are not. Therefore, these must be naturally warm areas.

The same technique of measurement has been applied to determine the temperature of small areas of the lunar surface. In this way, it has been discovered that several volcanic mountain peaks are warmer than the surrounding plain both during the lunar day and during the lunar night.

LUNAR CRATERS | the moon's circular mountains

Although man's knowledge of lunar features is now partly based on first-hand exploration, a trip to the moon is not required to obtain a clear view of its surface. The many excellent photographs taken during the Surveyor and other missions provide a very clear picture of the lunar landscape. Telescopic studies can also be made, between the fifth and tenth days following the new moon, by examining the region of the terminator (that region close to the twilight zone where the sun's rays fall obliquely). The most outstanding reliefs appear to the south.

This southern section of the lunar surface is quite mountainous. The mountains appear to overlap one another, forming a very irregular surface. The most striking feature, however, is that these mountains appear to be circular in shape; they are sometimes topped by a conical peak, at other times by a fairly smooth plain, and in some cases by other mountains of similar form. Still other forms, at first sight, resemble the Earth's terrain and are commonly called mountain chains.

Finally, there are the large plains that Galileo inaccurately labeled "seas" because, through his crude telescope, their dark, smooth surfaces resembled water-filled basins. The Apollo 11 astronauts firmly and thoroughly proved that water, in any form, does not exist on the moon.

An examination of lunar surface details and the data collected by the Apollo astronauts allow the construction of likely hypotheses explaining the phenomena that gave the satellite its present appearance.

THE CIRCULAR MOUNTAINS

Scattered over the lunar surface are ring-shaped mountains, some steep-sided, others sloping gently both inward and outward. Because of their resemblance to the shape of Earth's volcanoes, these are called craters. The largest are hundreds of miles in diameter. The smallest —inches across—were discovered when man first set foot on the moon.

THE GIGANTIC CLAVIUS CRATER—The outlines of this enormous crater appear on the southern terminator around the ninth or tenth day of lunation. Known as Clavius, its diameter exceeds 300 km (about 200 mi). Its outline is indented by other craters, which probably formed at a later date. Craters are visible in its interior, as well as on its steep and rugged outer edges.

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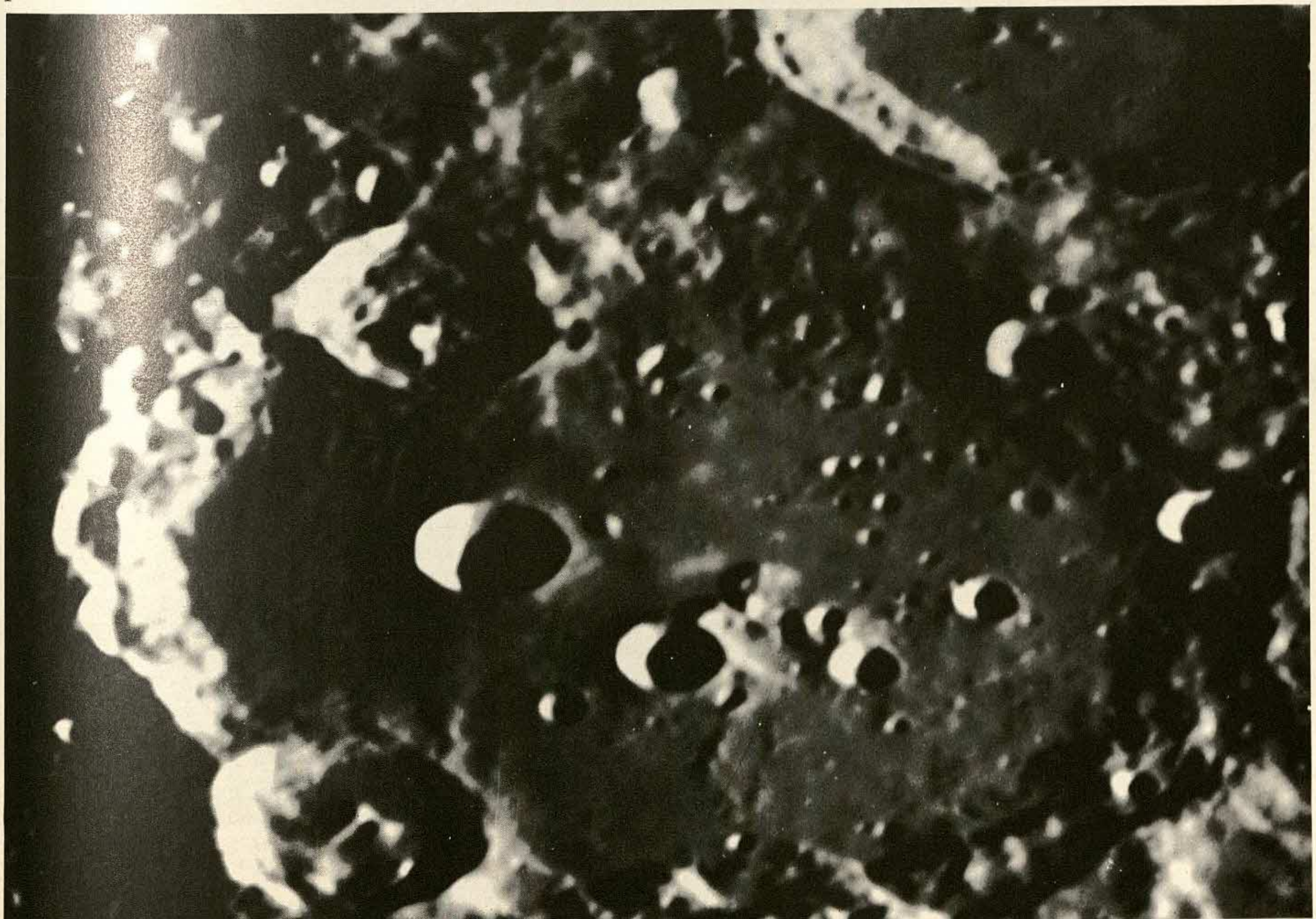


2

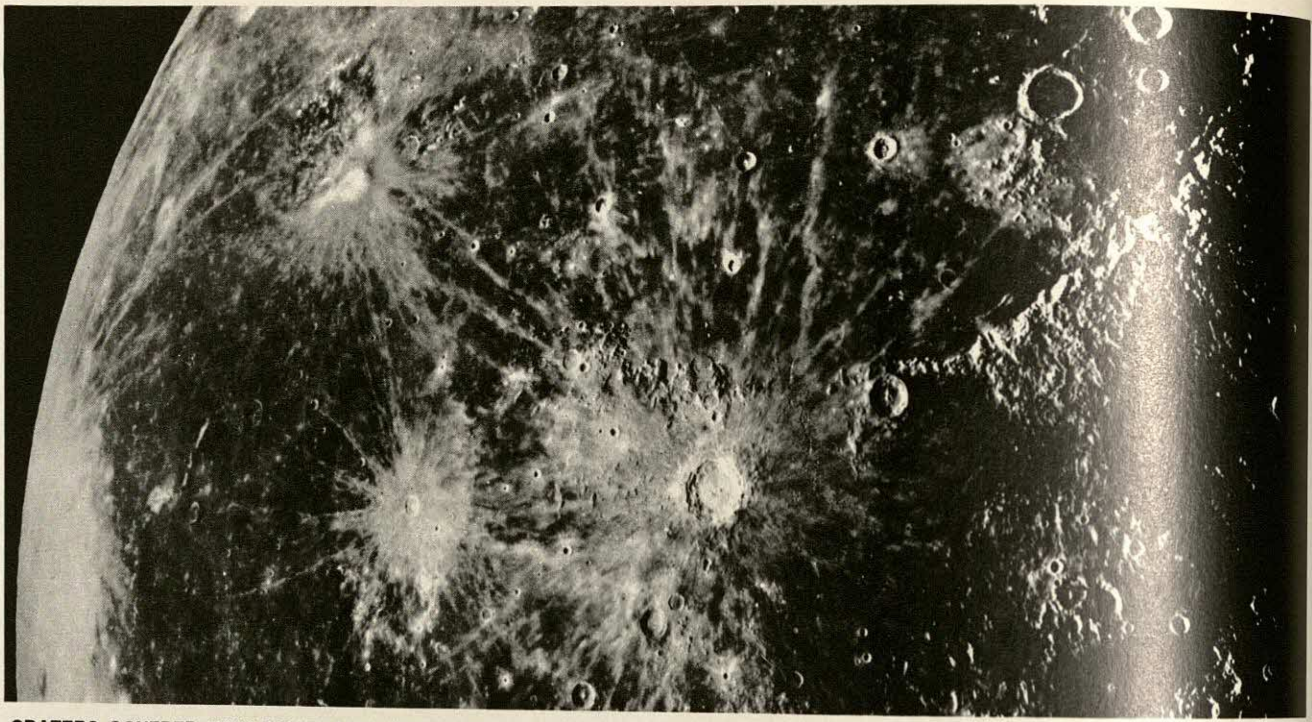
AN ANCIENT CRATER—Near the southern border of the Sea of Rains (also known by its Latin name, Mare Imbrium) are three adjacent craters. Copernicus and Eratosthenes appear as strongly marked reliefs; between them is Stadium. Copernicus and Eratosthenes are typical young craters; they have a precipitous form and have not been altered by smaller craters. Stadium, on the other hand, appears to be scarcely above the surface of the plain that separates the other two. Stadium resembles a sand castle that has been subjected to a long period of rain.

Many reasons exist for suspecting that craters like Stadium are ancient. They would have been subjected to such destructive phenomena (believed peculiar to the moon) as continuous meteorite bombardment and, in distant eras, remelting caused by the invasion of magma pouring out over the surface.

The term "ancient" refers to the scale of time of lunar history, but what is the age of the Earth's only natural satellite? This question remained a mystery until scientists were able to examine and date samples of moon rock brought back by the Apollo astronauts. These samples have been found to be as old as the oldest known Earth rock—approximately 4.5 billion years.

TYCHO'S LARGE RAYS — This crater was named after the Danish astronomer Tycho Brahe. Numerous light-colored rays branch out for great distances from its center, standing out clearly against the background of the lunar surface. Some rays extend as far as the Mare Frigoris (Sea of Cold)—almost antipodal to Tycho—while others extend toward the invisible hemisphere of the moon.

4



CRATERS COVERED WITH LIGHT ASH—The craters shown here—Copernicus, Kepler, and Aristarchus—are surrounded by rays similar to those of Tycho. The surfaces of the craters and the rays are so light that they are visible even if illuminated only by the weak light reflected from the Earth. These rays were almost surely formed by the expulsion of material from the craters from which they radiate, but it is not certain that they were formed as part of the same process that formed the craters themselves. However, a comparison with terrestrial volcanoes indicates that this is possible. During recent eruptions on Earth, volcanic matter has been hurled as far as 40 km (about 25 mi). In the absence of air resistance, it is possible for such volcanic ejecta to reach double this distance. On the moon, the acceleration of gravity is six times less than on Earth, and the range of a volcanic projectile is greater in proportion. Thus, the same forces that constructed the Earth's volcanic reliefs could also have constructed the lunar surface reliefs and the long lines that radiate from the craters.

5

THE ORIGIN OF LUNAR CRATERS—Meteorites striking the solid surface of a planet at a high velocity form craters. The graph (Illustration 5a) shows the depths of such craters in proportion to their diameters. To the lower left are points corresponding to very small craters (some of them artificially produced in the laboratory); in the center are points corresponding to craters produced by the fall of meteorites on the Earth's surface; to the upper right are points corresponding to lunar craters. A fairly regular, continuous curve joins all these points, giving some confirmation to the hypothesis that the lunar craters were produced by the bombardment of meteorites from space.

A meteorite striking the surface of a planet acts like a bomb containing a powerful explosive. While moving in space, the velocity of the meteorite is extremely high. When the meteorite strikes a solid surface (Illustration 5b), it penetrates to a certain depth (particularly when it is not slowed by the atmosphere, as it would not be in the case of the moon). Immediately after the penetration, the motion of the meteorite's molecules, previously contained within the meteorite itself, is disrupted. The molecules are detached from each other and their motion becomes chaotic, like that of gas molecules. At this point (Illustration 5c), the mass of the meteorite is transformed into a mass of gas at an extremely high temperature, and exercises an intense pressure on the walls of the cavity created by its penetration. The sudden dilation of this gas causes an explosion, spreading the surrounding material.

One objection to this hypothesis concerning the origin of lunar craters is that, if the moon had been subjected to an intense meteorite bombardment, the same thing should have taken place on the Earth, where there are no apparent signs of such an occurrence. However, in recent years, vestiges of innumerable meteorite craters similar to lunar craters have been discovered on Earth. Therefore, it may be argued that the region of space occupied by the Earth and the moon was subjected to an intense meteorite bombardment, and that over the course of a few million years, the forces of erosion destroyed all but a few traces of this bombardment on Earth. The hypothesis of a meteorite origin of the lunar craters does not exclude the possibility that meteorite penetration may have set off eruptive phenomena, thus generating a considerable invasion of magma onto the lunar surface. Further exploration of the composition of the moon's surface will undoubtedly provide clues to the mystery of the lunar craters.

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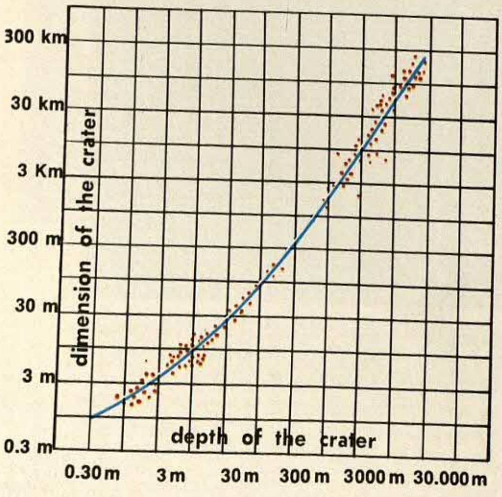

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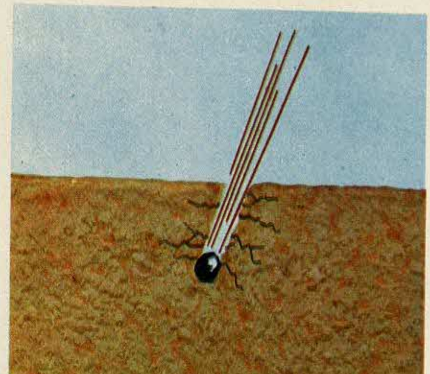

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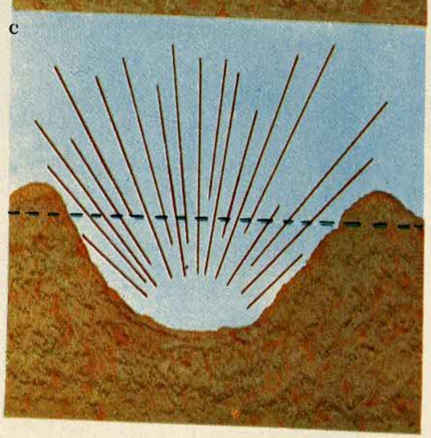


LUNAR WALLED PLAINS | a mystery not yet understood

A photograph of the moon's surface shows lunar mountains in the form of circular embankments almost identical in appearance with the moon's craters but with perfectly flat central floors, suggesting that they may once have been filled with liquid. Such features are called ring plains or, more generally, walled plains.

The craters Clavius, Copernicus, and Eratosthenes are typical of their class. The walled plains, a class of lunar formation typified by the ring plains Plato, Archimedes, and Ptolemaeus, are described in the present article. Plato and Archimedes have diameters of about 100 km (about 62 mi), and Ptolemaeus, 140 km (about 87 mi). Others are even larger; a person standing at the center of such a plain could not see its surrounding mountain walls because of the curvature of the lunar surface.

An important and typical feature of a walled plain is that the floor—that is, the plain—is absolutely flat. In rare cases small craters can be seen located on the flat floor. The outer slopes of the encircling walls are similar to those of other lunar craters; its inside slopes are steeply inclined. They look as if the ring plains had once been full of liquid that, when draining away, eroded the inner slopes. A few large walled plains, such as that of the crater Pitatus, have a small peak near the center.

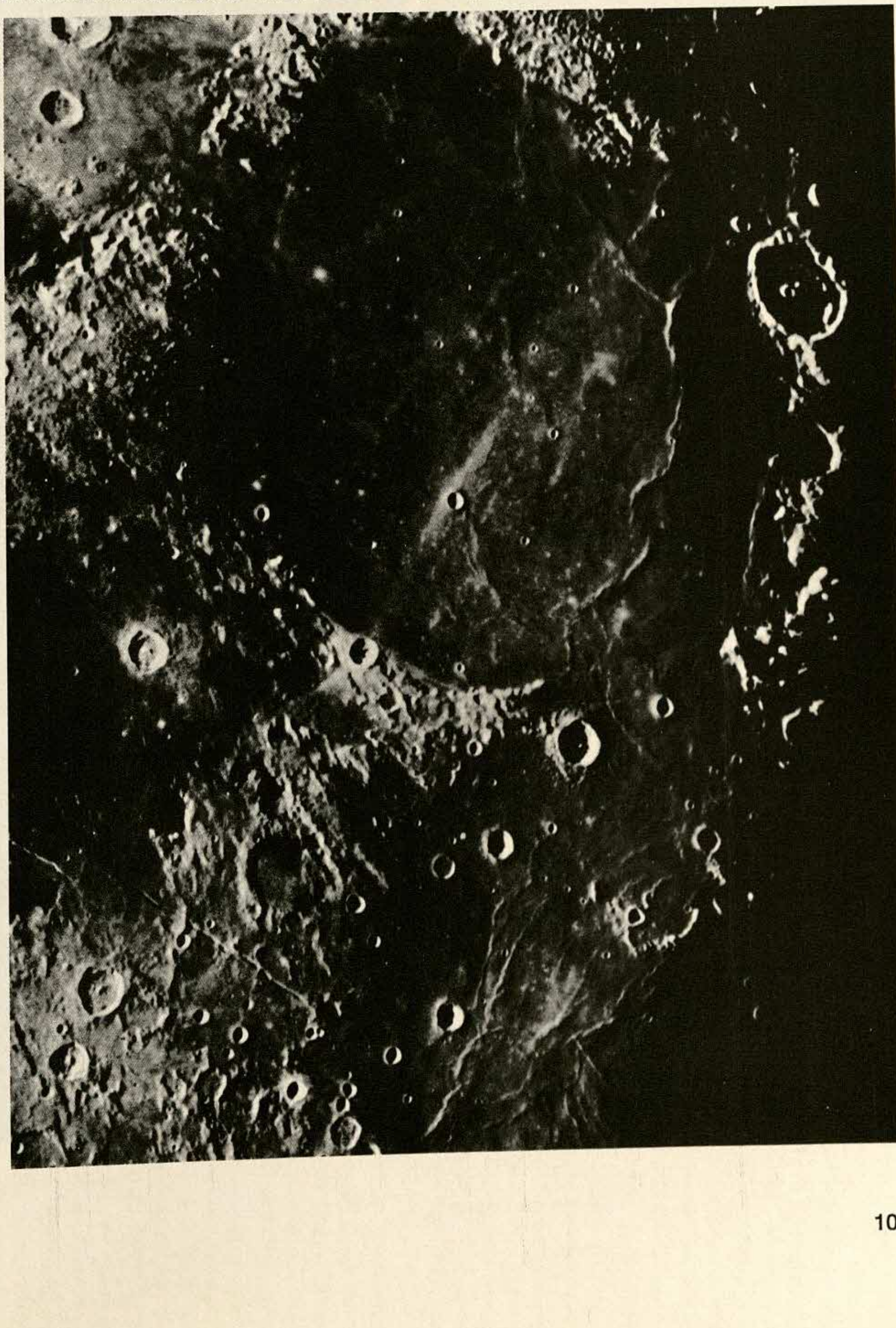
The circular shape of the walled plains and the craters surrounding them is not particularly surprising when it is considered that they are thought to be formed by the impact of meteorites or by lava eruptions. However, with such a theory of origin, it is difficult to explain the formation of a hexagonal or a polygonal crater. The best example of this is the crater surrounding the ring plain Ptolemaeus; the crater has six almost perfectly straight sides. Other examples can be seen in photographs of the moon's surface. Sometimes the walls of a ring plain, instead of being segments of straight mountain chains, are made up of arcs that intersect at the vertices of a hexagon.

The smooth flat floor of a walled plain is similar in many respects to that of a lunar mare. In each case the surface is dark, as is clearly seen around the tenth night of a lunation in the Mare Imbrium and the nearby walled plain Plato. The main difference between the walled plains and the regular maria is one of size; the maria are generally larger.

A clear distinction between the walled plains and the maria or seas is difficult to make at any point on the moon's surface, as can be seen by looking at lunar photographs. A list of the large walled

1

MARE SERENITATIS, THE SEA OF SERENITY—The flat smooth bottom of a walled plain on the moon is very similar to the flat smooth bottom of a lunar mare or "sea"; thus a clear distinction between the two is difficult to make. The large sea shown here with a number of markings called wrinkle ridges is the Sea of Serenity (Mare Serenitatis). Part of Mare Tranquillitatis can be seen at bottom right of the photograph.



plains can be made in order of increasing diameter, ending with the largest ones such as Schickard, which is more than 200 km (about 125 mi) across. The list can be extended by adding features of the moon's surface that are classified as seas. For example, Sinus Iridum (Bay of Rainbows) is clearly bounded by a circular rampart but with one third of the ring missing; its diameter is about 250 km (about 155 mi). Mare Crisium (the Sea of Crisis) has a diameter of 450 km (about 280 mi); then, there are other small regular seas or maria of increasing size up to the very large ones such as Mare Imbrium, the largest. The margin of this last sea—now incomplete but including long mountain chains—is circular, resembling an ancient remnant of a now partially destroyed gigantic ring.

There are no differences in form between the contours of Sinus Iridum, Mare Crisium, and smaller walled plains. Even the walls of Mare Crisium are polygonal.

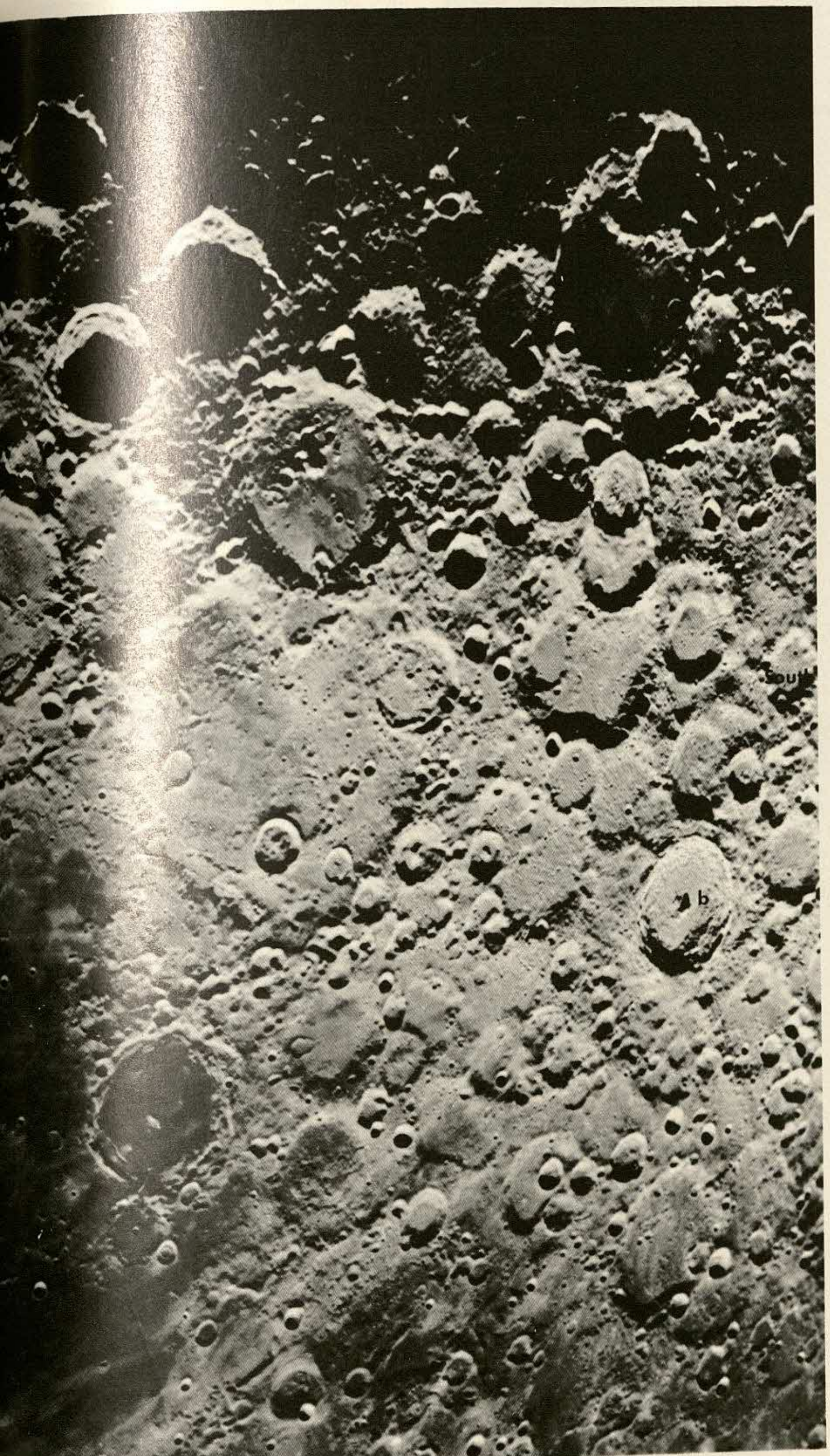
Mare Imbrium is bordered by curved mountain chains (such as the Apennines and the Caucasus mountain ranges) that spread along arcs of the same circle, one after the other. The southeast border is the Carpathian chain, near the crater Copernicus. The northeast border is not a true mountain chain; nevertheless, it is formed like an arc and is situated along the same circle as the chain of mountain arcs.

LAVA INVASIONS OF MARE (SEA) BASINS

In general, the floors of the lunar maria and of the walled plains seem to be darker than the rest of the moon's surface. The floors of the maria and the walled plains appear to be lower than the rest of the surface and may be called, collectively, basins.

The composition of the rocks that make up these flat expanses is thought to be different from the composition of those that make up the rest of the moon's surface. Probably the rocks of the lunar basins are similar to the Earth's basalt and, therefore, can become fluid at temperatures at which other types of erup-

2a



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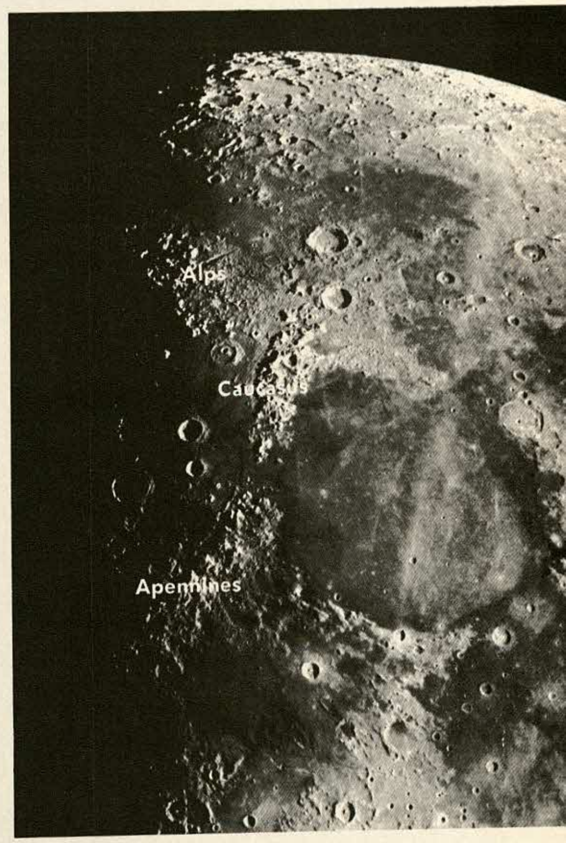

THE WALLED PLAINS—These plains are common forms on the moon's surface. Although they are similar in many respects to craters, the interior floors are completely flat and are rarely broken up by small craters. The ramparts of some walled plains are polygonal in form like those of Ptolemy (Illustration 2a), but most of them are circular. This photograph, taken at the time of the last quarter, shows a portion of the moon between Ptolemy **a** and Tycho **b.** Illustration 2b shows the northern part of the moon with the mountain chains (Alps, Apennines, and Caucasus mountains) that border Mare Imbrium. The complete mare shown in Illustration 2b is Mare Serenitatis.

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tive rock are already solid or at least extremely viscous.

When the surfaces of the maria are viewed in light that arrives almost from the lunar horizon, near lunar sunrise or sunset, it is possible to see that the nearly flat surface may here and there show slight undulations like frozen waves. Such undulations are clearly visible in Mare Imbrium, where the surface shows marks like ripples, as if a wind had blown from west to east, stirring up the

3

MARE IMBRIUM, THE SEA OF DREAMS—This mare is the largest on the moon's surface. The part of its edge outlined by a series of curved mountain chains resembles the ancient remnant of a partially destroyed gigantic walled plain.

surface of a liquid sea that had then immediately frozen. In reality, no such wind could have existed and these waves may have been produced by a flow of magma across the mare. Similar wave-like ripples can be seen in other flat areas.

The impact of speeding meteorites against the lunar soil at a time when the moon was not completely solid may have perforated a solid crust and thus caused the formation of some craters. Magma may then have flowed out of such holes; if the viscosity of the magma was high enough and if it contained sufficient gas, it could have formed the small cones, resembling terrestrial cones of scoriae and lava, that can be seen here and there. Some of the craters may have formed in this way. Perhaps very hot fluid magma flowed out, invading and filling certain craters.

Before solidifying, however, the liquid magma may have eroded the inside walls of the crater; it may have remelted some of the rocks that it lapped against, thereby collapsing them into the basin. Something similar can happen in the calderas of the Earth's volcanoes that erupt fluid magma. This could account for the walled plains having flat floors and craggy inside walls, although the enormous size of even the smallest of these plains does not fit this explanation. It is difficult to account for such large features in this way unless the lava was produced on a vast scale. Most of the Earth's calderas are quite small in comparison with the smallest of the walled plains.

The large lunar seas may have been produced by even greater flows of lava that would have destroyed any pre-existing relief. However, such a catastrophe would probably have destroyed the whole moon at the same time.

The isolated peaks Pico and Piton in the Mare Imbrium, and the mountains known as the Straight Wall, may be the remains of once higher features that were eroded by the heat of fluid lava at their bases. It is also possible that the great roughness of the mare surfaces that can be seen here and there is partially due to obstacles met by the lava during its flow; these may have been rocks from the mountains buried in the lava itself.

WARGENTIN, THE CRATER FILLED TO THE BRIM

One example supporting the idea that the walled plains were once flooded by lava is the Wargentin crater, which is circular in form, flat in the center, and filled with lunar material up to the brim, a good 300 m (about 1,000 ft) above the surrounding plains. Perhaps a small portion of lava may have overflowed, splashing out over the sides. Such an event is not uncommon on the Earth. Terrestrial magma is always rich in gases under pressure that readily expand and push it up and out at the surface. This is why magma can flow from the mouth of a volcano even when its outlet is several miles above the surrounding land.

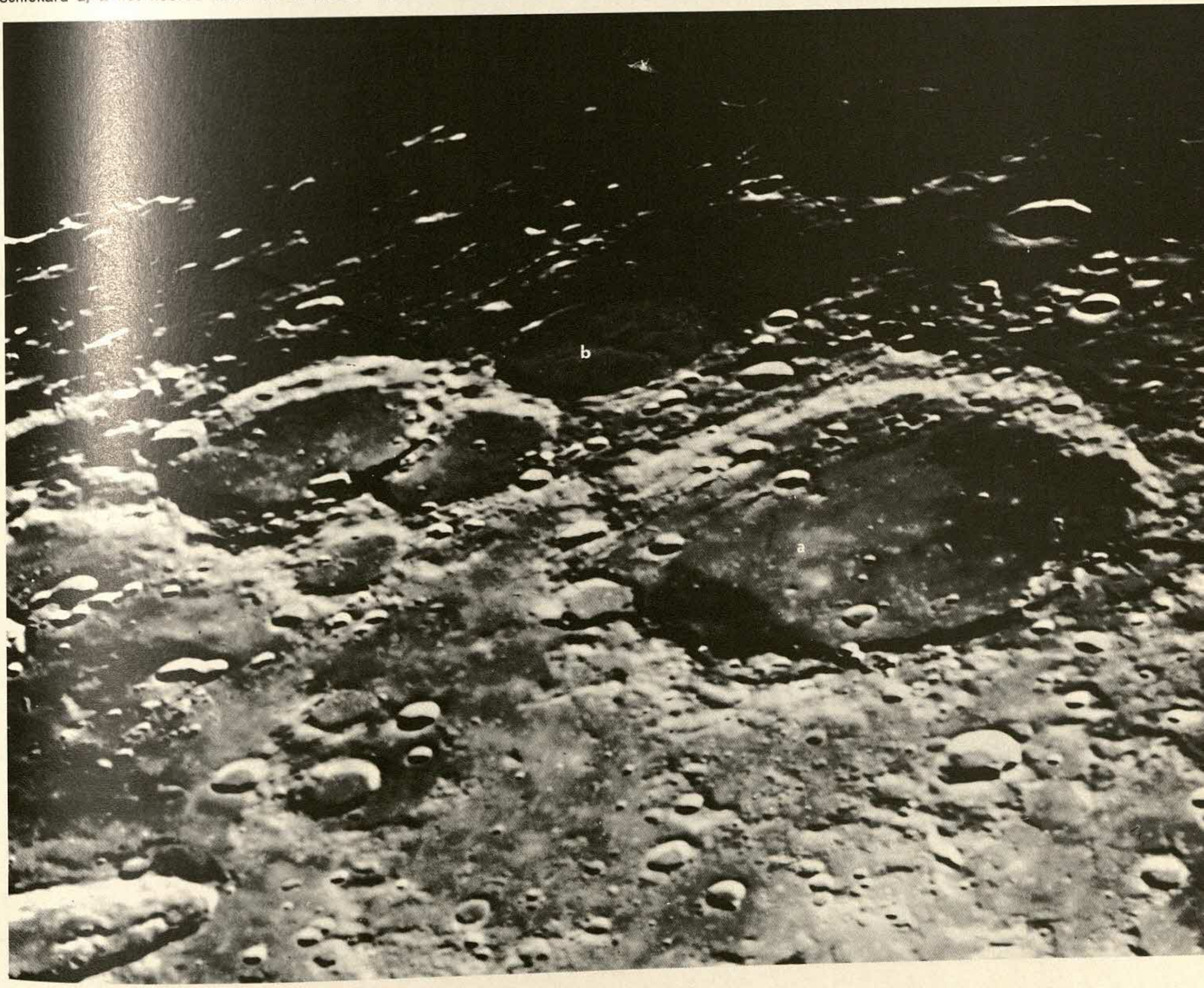
LUNAR RELIEF AND THE MEASUREMENT OF HEIGHTS ON THE MOON

Reference has been made to the heights of the lunar mountains, and to the walled plain's walls relative to the crater floors and the surrounding plains. On the moon, it is impossible to refer to a level that would correspond to sea level on the Earth, for the simple reason that no true sea and, therefore, no corresponding level of reference exists on the moon. Lunar seas, the maria, are large plains of solid matter, each probably at a different level as a result of formation at different times in the moon's history.

Nevertheless, it is possible to make precise measurements of the heights of a lunar mountain above its immediate surroundings. In carrying out such measurements by the "shadow method," the angle of the sun at the time of the measurement above the horizon at the location of the peak must be known. Then it is possible to determine the length of the shadow cast by the mountain on flat ground at its foot. A right triangle is drawn—a triangle in which one side represents the horizontal length of the shadow on the moon, another side the vertical height of the mountain, and the angle of the Sun above the horizon is the acute angle opposite to this side. The height of the triangle represents the height of the mountain on the scale of the horizontal shadow, and it can now be measured from a drawing or calculated.

4

LUNAR CRATERS—Shown in the photograph are some extensive lunar features such as Schickard **a,** a flat floored lunar crater more than 200 km (about 125 mi) in diameter, and Wargentin **b,** which is notable because the floor of the crater is raised about 300 m (about 1,000 ft) above the surrounding lunar surface, perhaps because the crater was filled with lava rising up under pressure from below.



THE PHENOMENA OF THE SOLAR PHOTOSPHERE

When Galileo pointed his telescope at the sun and discovered spots on it, his detractors ridiculed the find. They argued that, since the sun was by definition and tradition a perfect body, the telescope must be faulty. They were wrong, of course, for Galileo's instrument clearly showed him something that had never been observed before: sunspots.

If the sun is observed through a smoked glass, it appears as a very bright and almost uniformly luminous disk. Only rarely can a sunspot of large size be seen. Actually, many points on the solar surface are covered with small, dark spots of irregular outlines and varying sizes. These can be seen only under magnification.

SUNSPOTS

Sunspots appear to be dark because the gas of which they are composed is cooler than the same gas in other parts of the photosphere. Solar gas acts like a black body, and emits less light at lower temperatures than at higher ones. In the spots, the solar plasma reaches about 4,000° C (about 7,200° F) compared to the almost 6,000° C (about 10,800° F) of the rest of the photosphere. This temperature difference causes a difference in light emission by a factor of 5 or 6. Even though this light emission is less than that of the rest of the photosphere, its spectrum can be studied. It shows the same lines and the presence of the same elements that are observed in the photosphere at large. However, the lower temperature of the spots makes it easier to find the atoms of gas that have combined to form molecules or radicals; therefore, the spectra of the spots are particularly rich in molecular bands.

Continued daily observation of a sunspot seems to indicate that it moves around the sun. Actually, the sun itself rotates on its axis, taking the spot with it. If the spot lasts long enough, it disappears beyond the edge of the sun and, if its life-span is at least a month, it will reappear on the opposite side after a complete rotation.

Because the spots are the only distinctive marks that appear on the sun's surface, early astronomers used them to determine the period of rotation. Then it was discovered that spots near the equator completed a circuit of the sun in about 25 days, while those at a latitude of 40° north or south took two-and-a-half days longer. Because all the spots at the same latitude completed the circuit in the same time, it was concluded that the sun did not rotate as a rigid body, but rather as a fluid sphere composed of different layers floating one above the other.

This difference in velocity of solar rotation according to latitude was confirmed by spectroscopic observation. A spot that is followed during a complete rotation appears smooth as it is seen edge-on near the solar edge; no depressions or prominences of the cold solar material are evident. Sometimes, however, other phenomena are associated with the spots.

2

THE ROTATION OF THE SUN—Observation of a sunspot on successive days gives an estimate of the rotation of the sun. In about 14 days, a spot is carried from one edge to the opposite one. It can be observed for more than one rotation if its life-span is long enough.

A GROUP OF SUNSPOTS—Sunspots are often isolated but sometimes appear in groups. This group of spots—one of the largest ever observed—appeared on March 17, 1951. The centers of the spots are dark because they are cooler than other areas of the spots.

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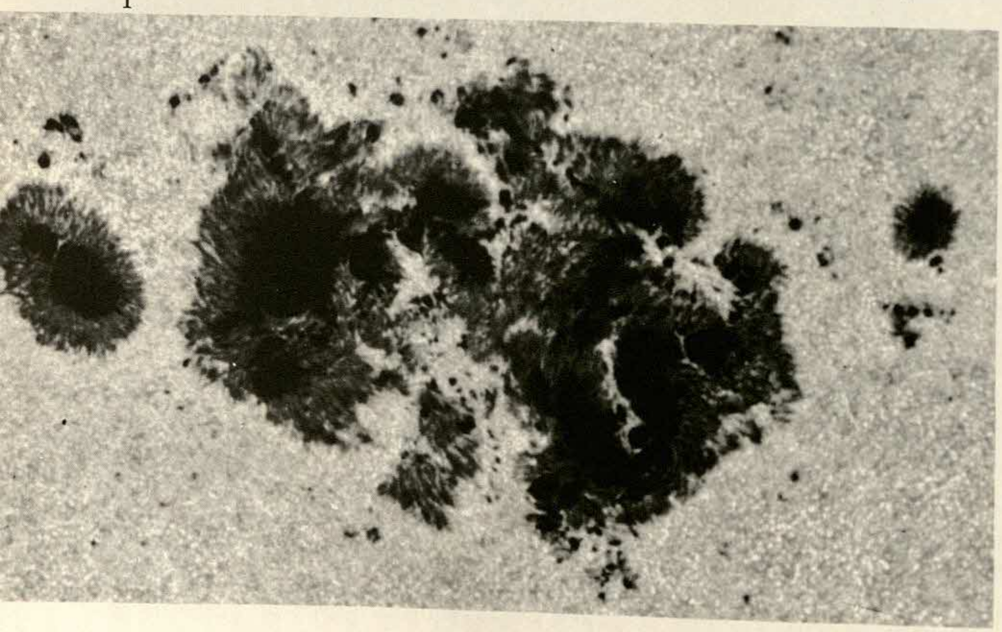

SUNSPOT CYCLES

On some days, the sun exhibits a great many spots; on other days, not a single spot can be seen, even with the most powerful instruments. The times when sunspots are abundant and those when they are rare occur in phases. These phases alternate over a period of about eleven-and-a-half years. Because the discovery of this cycle was made in the last

THE BUTTERFLY GRAPH—Dark areas in the graph show the abundance of sunspots in successive years at different solar latitudes. Approximately every eleven years, the frequency of appearance is repeated. At the beginning of a cycle, the spots are at high latitudes; at the end of the cycle, they are a few degrees from the equator.

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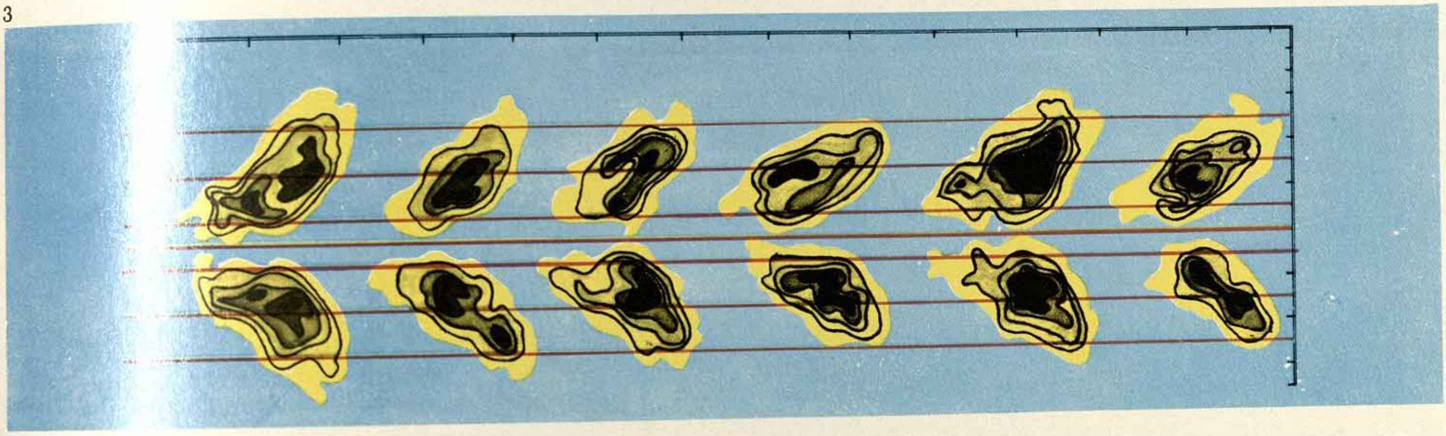

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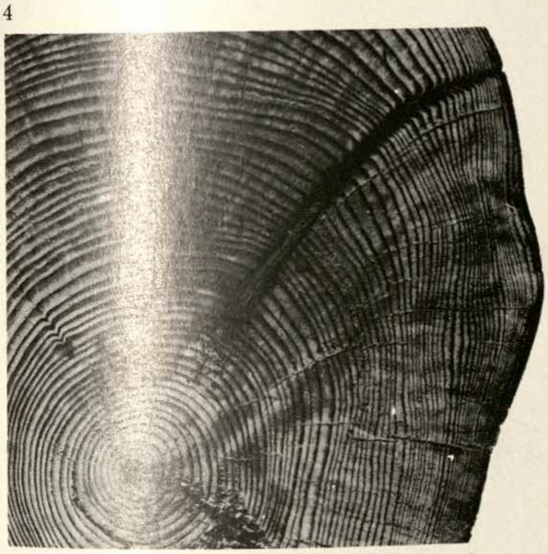


SOLAR INFLUENCES—The effects of the sun on the Earth are largely unknown, but it is certain that the eleven-year sunspot cycle has an influence on the climate. This influence determines the variation in the growth rate of wood, as shown in this cross section of a tree trunk.

century, too few cycles have passed for a precise measurement to have been made. Furthermore, the cycle is not strictly periodical; it has been as few as eight years and as many as thirteen.

Astronomers have tried to find a relationship between the sunspot cycle and the intensity of the radiation that the sun sends into space. It has not yet been possible to measure any appreciable variations in the intensity of solar radiation. However, observation of phenomena occurring on Earth that are influenced by the quality and quantity of solar radiation confirms that changes do take place in this radiation during the eleven-year cycle. For example, growth rings of centuries-old trees show patterns that are wide and narrow during periods of eleven years. This periodic variation in the speed of growth of vegetable life can even be found in the growth rings of fossil plants that lived hundreds of millions of years ago.

These observations provide very strong evidence that the sun that shone on the Earth in the most remote geological eras was similar in its physical characteristics to the sun that shines today.

THE BUTTERFLY GRAPH

An interesting study of the sunspot phenomena can be made by constructing a graph with time as the axis of the abscissa and the solar latitude as the ordinate. Every time a spot appears, a point, corresponding to the date and the latitude at which the appearance occurred, is marked on the graph. This will disclose an interesting and curious fact. During the eleven-year cycle, the spots appear, little by little, at ever lower latitudes. At the beginning of a cycle, the first spots are observed at a solar latitude of about 40° north or south. Subsequent spots appear successively closer to the equator. The final spots in a cycle are found up to 5° above or below the equator. Meanwhile, other spots, belonging to a new cycle, appear at high latitudes.

A graph drawn in this manner assumes a characteristic appearance—thus the name "butterfly graph," because of the shape of the marked areas.

THE STRUCTURE OF SUNSPOTS

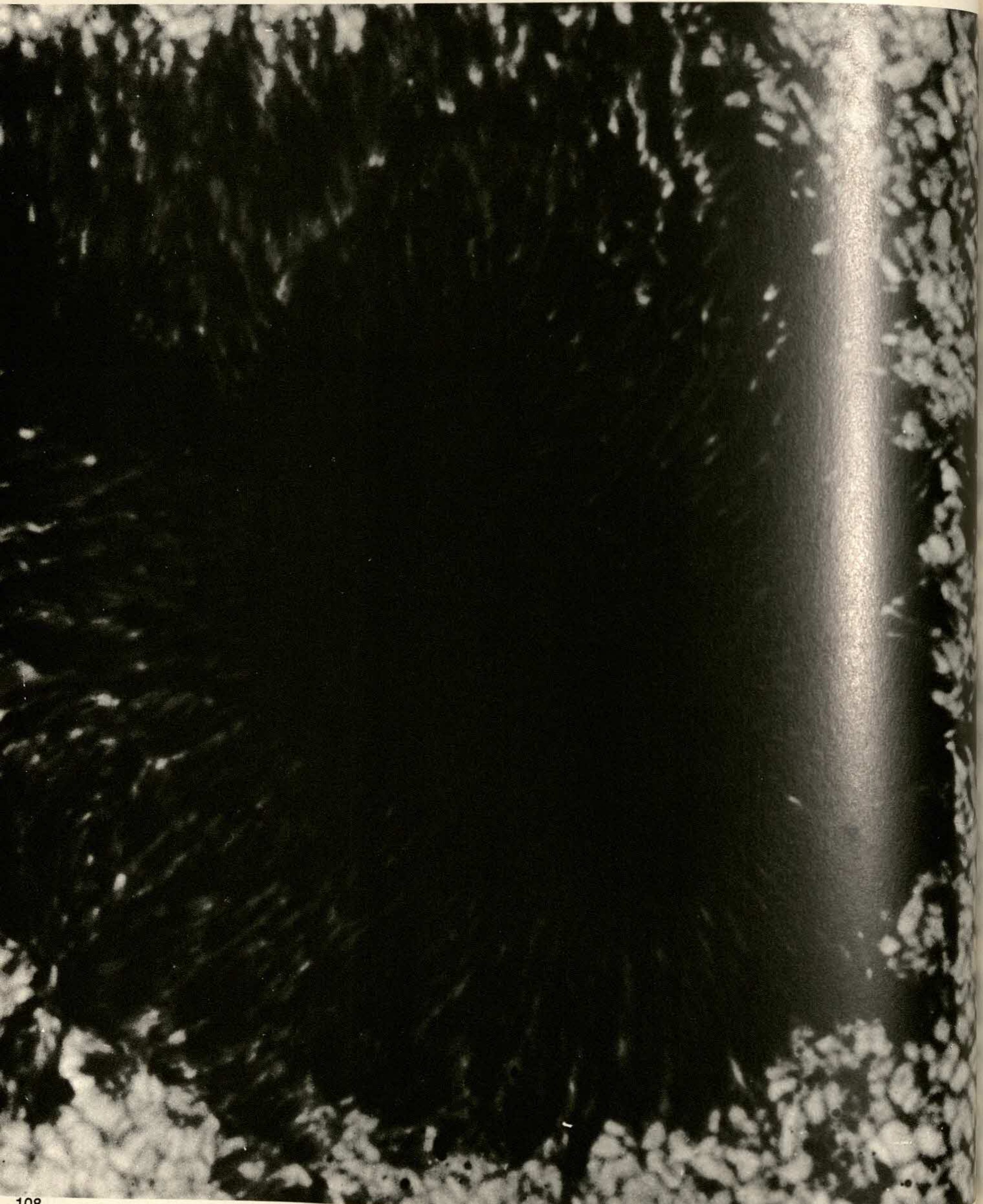
When observed through a telescope, smaller sunspots appear uniformly dark. Their edges seem to be slightly indented and their shape is always more or less circular.

The edges of larger spots are often broken up, and the spots are darker at the center than at the edges, although there is no lessening of intensity. The darker, homogeneous center is the umbra; the lighter outer part, which is furrowed with radial filaments, is the penumbra. The penumbra is lighter because its temperature is between that of the cooler center spot and the surrounding photosphere.

Sunspots are often grouped together in varying numbers; sometimes a group contains tens of spots. Groups of spots appear almost exclusively during the pe-

THE SUN FROM A HEIGHT OF 32 KM (ABOUT 20 MI) ABOVE THE EARTH—This photograph, undistorted by low-level atmospheric turbulence, was taken through a telescope carried by a balloon to an altitude of 32 km (about 20 mi). The darker central part of the sunspot (the umbra), the outer filamentary part (the penumbra), and the granules are all clearly visible.

5



riods of maximum sunspot activity—approximately every eleven years. Away from the sunspots, which are known to be magnets, the solar atmosphere is in random, bubbling motion. This contrasts with the organized movements enforced by a sunspot region—possibly because of the action of magnetic fields.

Before attempting to understand the possible origin of sunspots, it is necessary to be familiar with many characteristic phenomena of solar activity.

GRANULES

Observation of the solar surface with a telescope having a resolving power of at least one second of arc shows that the photosphere, rather than being uniformly brilliant, is dotted by a myriad of small points lighter than their background. Most of these dots are of the same size and have the appearance of grains of rice lying close together on a sheet of paper; thus their name: granules.

The dimensions of solar granules vary from 200 to 2,000 km (about 125 to 1,250 mi); larger ones are rarely observed, and the most frequently found size is about 960 km (about 600 mi). The granules are not permanent features of the sun's surface—they change shape in minutes. They are probably formed by the movements of the photospheric plasma, which rises and falls like a boiling liquid.

Until recent years, observation of granulation was imperfect because the presence of the sun itself causes perturbations in the Earth's atmosphere, greatly disturbing images seen through a telescope. Even under the best atmospheric conditions, granules are difficult to observe.

In order to study the evolution of granules, astronomers sought a way to avoid the atmospheric turbulence produced by solar radiation. They tried placing their instruments on high mountains so that the more rarefied atmosphere of these high places would yield less distorted images. This gave them a better but still inadequate view.

In 1955, a group of English astronomers ascended in a balloon to a height of approximately 18,000 feet, taking with them a 25-cm (about 10-in.) reflecting telescope. At that height, better images of granules were obtained than would have been possible at the same height on the Earth's surface. This is because the ground, which is heated by the sun's rays, in turn heats up the atmosphere in contact with it, thus creating inadequate conditions for observation.

SCHWARZSCHILD'S PROJECT

To make observations under still better conditions than his British colleagues, the American astronomer Schwarzschild constructed a telescope with movie camera capable of focusing on the sun; this device was then attached to an unmanned balloon. The balloon made many ascents to altitudes up to about 27,000 m (about 90,000 ft); the films show that the granules are formed on the photospheric background, that they grow in the space of a few minutes, and that once they have reached a sufficiently large size, they split up into smaller grains that, in turn, continue the growth pattern (Illustration 6).

In many kinds of astronomical research, balloon flights have many advantages over rocket flights. They last longer and cost much less, and the recovery of delicate instruments is much easier. The use of artificial satellites would make the task of recovery far more difficult, and also pose the problem of transmitting to Earth such complex information as data on the evolution of granules.

FACULAE

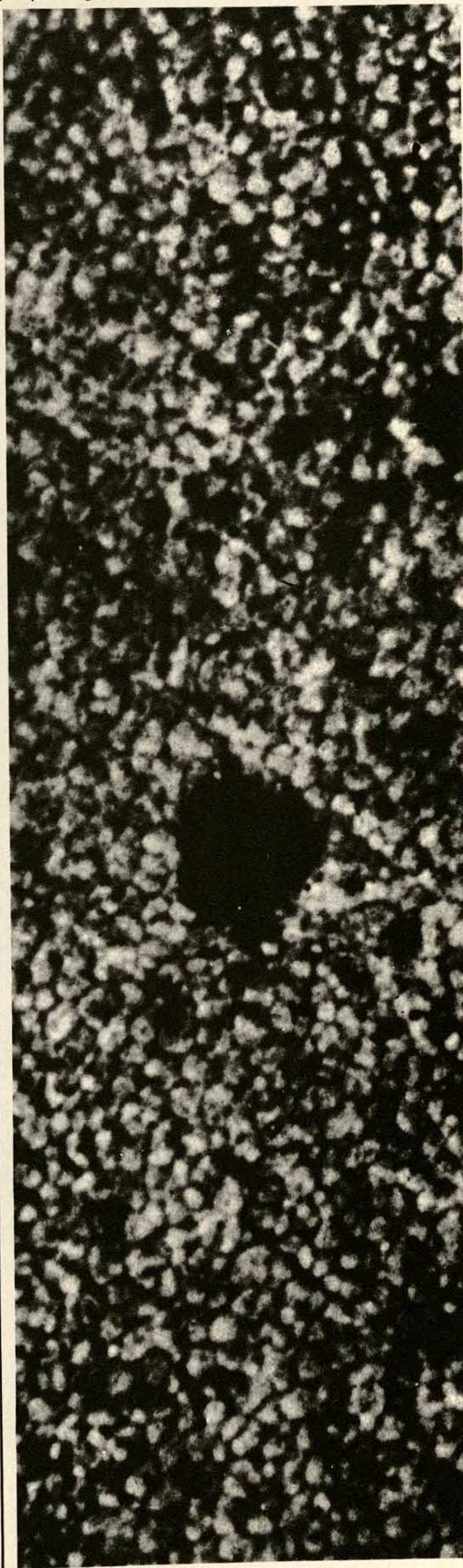
Galileo observed not only sunspots but also gases of varying extension that were more brilliant than the background photosphere. He gave these the name "faculae." Faculae are regions of the photosphere where the temperature of the solar plasma is higher than in other regions of the solar surface. The temperature variation may be only a few hundred degrees, but the hotter areas appear much more brilliant than their surroundings. The study of faculae is as important as the study of sunspots for an understanding of the sun.

Faculae are often close to sunspots; through the telescope, they appear as lighter regions in the form of irregular patches partially joined together. Sometimes, however, they appear in a region before sunspots appear, as a forewarning of the spots' impending appearance.

Faculae observed on the sun's circumference stand out better against the photospheric background than those observed elsewhere—they are slightly less intense in these areas since their light must cross part of the solar atmosphere. The faculae are raised slightly over the photospheric background; their light reaches Earth after having crossed a lesser atmospheric thickness on the Earth's surface.

6

SMALL SPOTS—Small sunspots are frequent; the smaller ones may be confused with spaces between granules. Small spots are frequently grouped together.



PROMINENCES OF THE SUN | tongues and arches of flaming gas

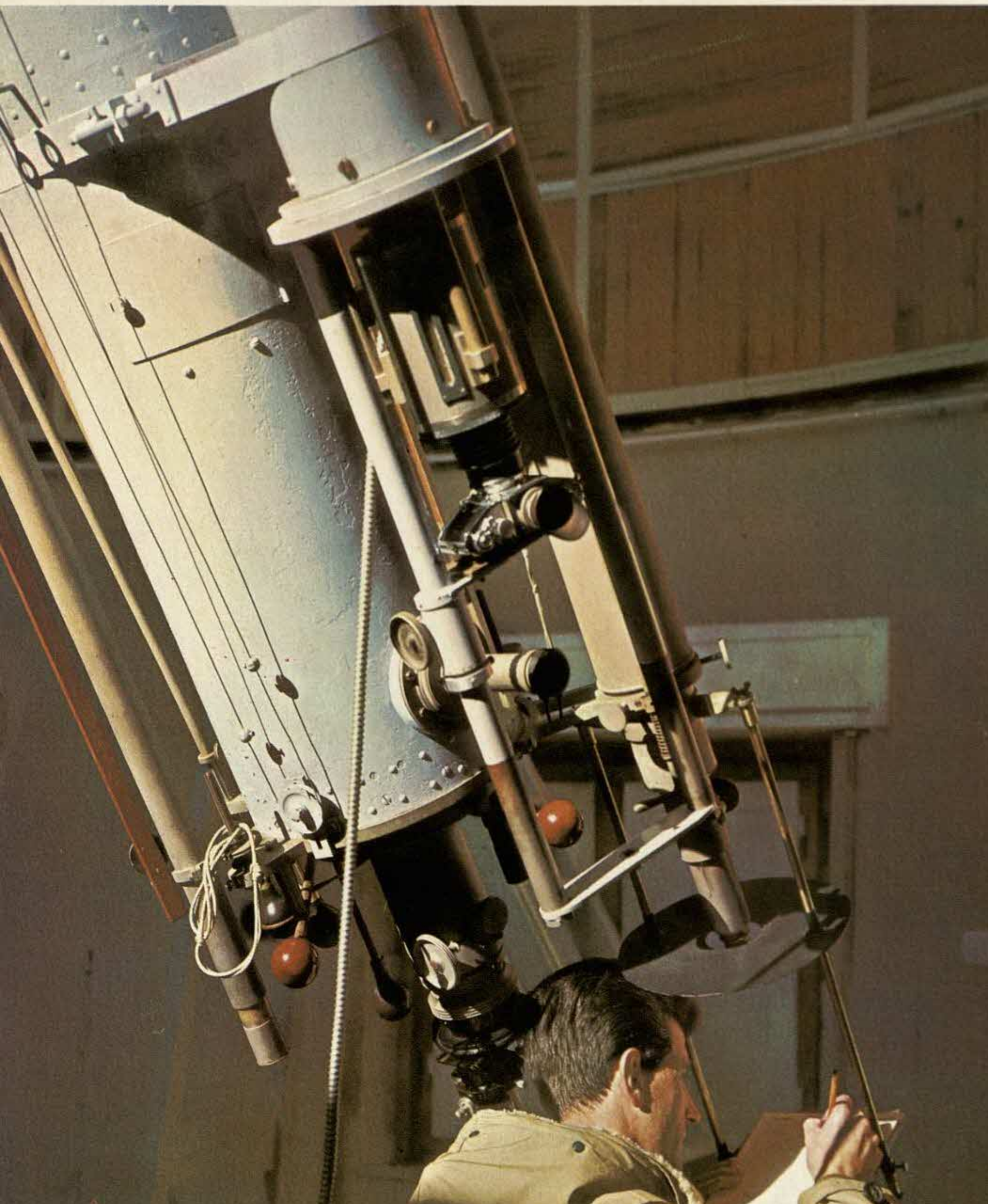
Many years before spectroscopic analysis was used to study the composition of the sun, it had been observed that during a total solar eclipse the black disk of the moon appeared bordered by an unusual, purple-colored edge—the chromosphere. From the chromosphere arose flaming projections that appeared to be composed of the same material as the chromosphere. These phenomena, which were visible on the solar surface, were given the name of solar prominences.

In 1868 the British astronomer Sir Norman Lockyer built an instrument designed for observation of solar prominences without the aid of a solar eclipse. The instrument consisted of a spectroscope illuminated by the sun and provided with an adjustable slit. First, the slit was focused on the sun's disk; the prism was then rotated until a hydrogen line appeared in the observation chamber. The image of the sun was moved in such a way that the edge of the solar disk fell on the slit. At this point the instrument showed the spectrum of the chromosphere—that is, the same hydrogen line as before, but of emission rather than of absorption. The remaining continuous spectrum disappeared, together with all its light and absorption lines.

Through such studies, it was established that the spectrum of the chromosphere contained very few lines in comparison with the many in the continuous spectrum of the photosphere, which contains lines of hydrogen, helium, calcium, and a few other elements. After the initial focusing, when the slit of the spectroscope was opened wide, monochromatic images of the chromosphere and of solar prominences became visible.

From the time of Lockyer's early use of the spectroscope, astronomers began a systematic study of solar prominences, which were soon discovered to change rapidly in shape, height, and size. Early spectroscopic observations of the prominences concentrated on the classification of their shapes and a study of their move-

1



2

SOLAR OBSERVATIONS BY TELESCOPE—Because of the enormous amount of light available from the sun, solar observations may be carried out with small telescopes. The astronomer (Illustration 1) is recording on paper the position of sunspots on the image projected by the sun.

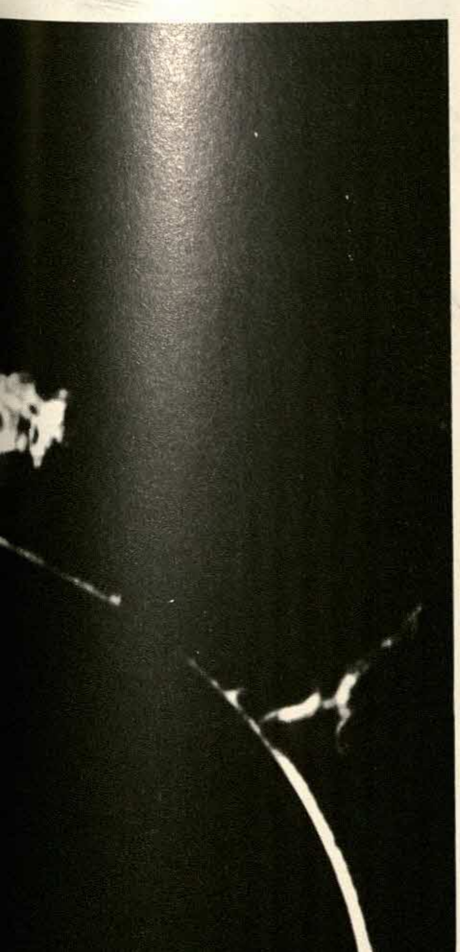
AN AVERAGE PROMINENCE—This prominence (Illustration 2), observed on December 25, 1938, is of average size but of high luminosity. Such an isolated photograph gives only a limited idea of the totality of a solar prominence.

ments, in order to furnish an explanation of their nature and origin.

CLASSIFICATION OF THE PROMINENCES

Today, study of solar prominences is made with telescopes equipped with a polarized monochromatic filter. In the last century Lockyer's more complicated instrument revealed that solar prominences appeared on the sun at all latitudes, close to the poles as well as at the equator, in contrast to the solar spots, which appeared most concentrated at low latitudes. Two types of prominences were identified. Some, known as eruptive prominences, showed a rapid movement away from the sun's surface. Others, which remained practically motionless and unvaried in shape as long as they were observed, are known as quiescent prominences. Aided by solar observations made in the twentieth century, astronomers eventually adopted a more detailed classification of the prominences, based essentially on their movement.

These later solar studies disclosed that some prominences, formed near the surface of the photosphere, have an initial height of some tens of thousands of kilometers; the height of some of these prominences eventually reaches hundreds of thousands of kilometers. The velocity of the rise may be as great as hundreds of kilometers per second. At times, the prominences diminish rather than grow during this ascent.



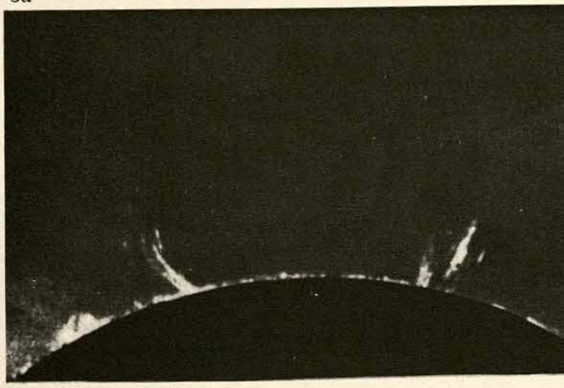
Taking as a hypothesis the assumption that a solar prominence is a jet of gas, the velocity of the gas should decrease as the prominence rises. Solar radiation, pushing outward on the atoms of gas comprising the prominence, could result in an increase in its velocity. A law of physics states that a force acting in a constant way on a mass will increase the velocity of the mass at a constant rate. Thus, it is possible that the motion of some prominences is chiefly the result of one of these two phenomena or possibly a combination of both.

Although prominences reach a height of between 50,000 and 600,000 km (about 31,000 and 373,000 mi) above the sun's surface, some have been observed at greater heights. In December 1938 a prominence thrust to a height of 907,000 km (about 564,000 mi), and in June 1946, a prominence—the largest ever observed—had the shape of a colossal arch with a base width of 600,000 km (about 373,000 mi). The arch of this giant prominence rose and finally dissolved. Traces of the prominence reached a height of 1,700,000 km (about 1,056,000 mi), equal to 1.22 times the diameter of the sun. During the ascent phase the velocity of the traces doubled about 140 to more than 300 kilometers per second (about 87 to 186 miles per second).

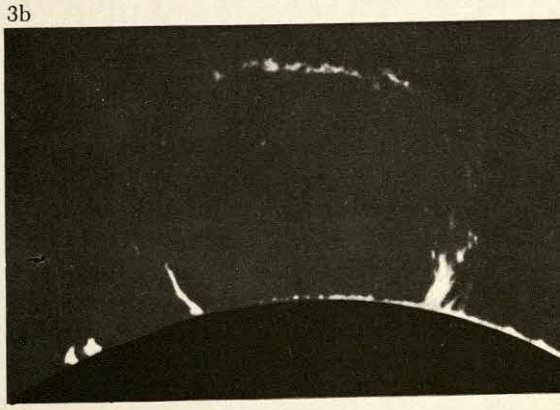
MOTION OF THE PROMINENCES

Solar prominences move both in latitude and longitude, thus changing their shape and size. The prominences often form near active areas—that is, the zones of sunspots and other photospheric disturbances. Solar prominences, therefore, are born near the sun's equatorial region, where such disturbances are most frequent. Furthermore, prominences that last for a period of two or three solar rotations stretch out into branches that redescend toward the photosphere, forming arches. These branches do not descend at random, but toward the point from which the prominence originated. The branches are usually positioned in such a way that the arch of the prominence is parallel to a solar meridian. If, however, the arch lasts longer than one solar rotation, it no longer remains parallel to a meridian but is positioned obliquely to it. This is due to the fact that the velocity of the sun's rotation is different at different latitudes. When solar rotation causes an arching prominence to project itself entirely against

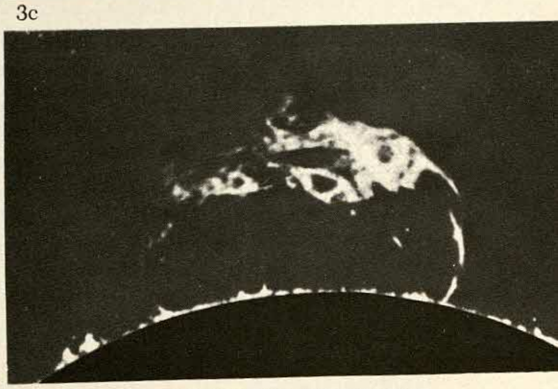
3a



3b



3c



EVOLUTION OF AN ERUPTIVE PROMINENCE—Successive photographs of this type of prominence clearly show its swift motion. This prominence rises from the surface of the sun at an extremely high velocity (Illustrations 3a, 3b, and 3c). The luminous gas of the prominence is not always in motion. The nature of this motion is not clearly understood.
As the prominence develops upward, its luminosity gradually decreases.

the solar disk, the prominence itself appears in monochromatic light as a dark filament.

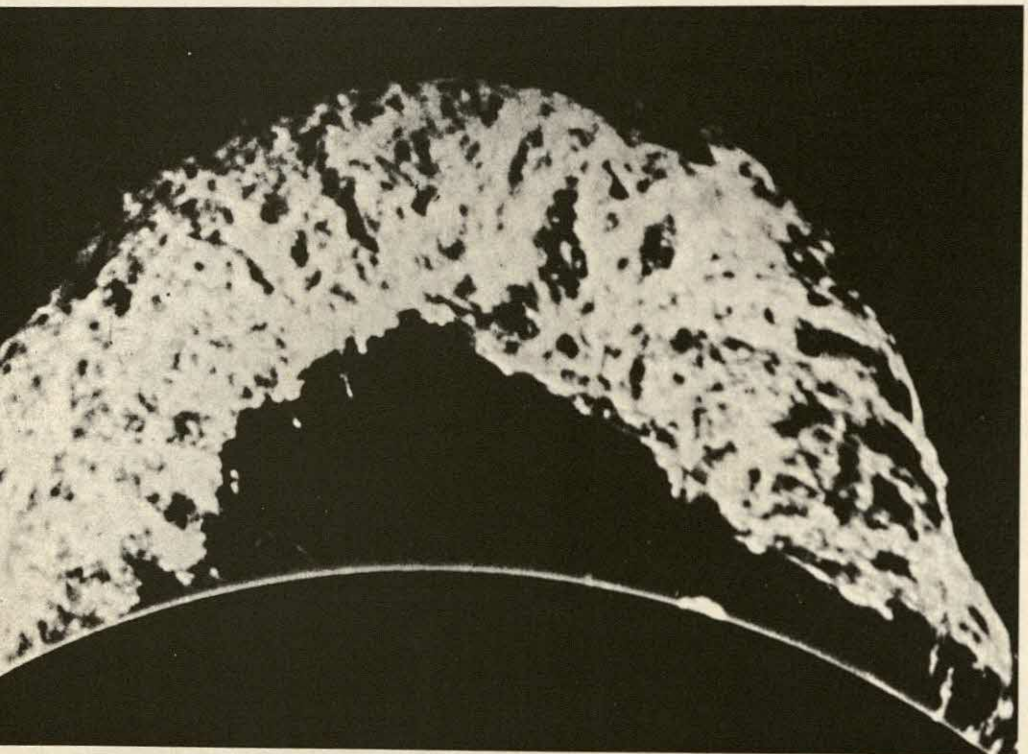
The rapid movements of a prominence observed on the sun's edge indicate the influence of magnetic fields. In fact, the prominences close to the spots can be seen rising along the lines of the magnetic field of the spots. Often the filaments of a prominence emerge from a spot, rise up along an arched trajectory and then descend toward a second spot or other center of activity having a magnetic field.

Inasmuch as the gas of the prominences is partly ionized, it is reasonable

ALMOST A FILM SHOT—Illustration 5a is a photograph of an extraordinary prominence observed October 8, 1920. It shows the rapid increase in the prominence's upward thrust of up to 300,000 mi. The superimposed white disk represents the size of the Earth.

Illustration 5b shows nine successive photographs of prominences observed on July 25-29, 1908.

4



LARGEST OBSERVED PROMINENCE—This arch-type prominence which appeared on June 4, 1946, is the largest yet observed. Its maximum distance above the sun's surface exceeded 800,000 km (about 497,000 mi), a distance more than the diameter of the sun. The shape of the arch is common to many prominences and is due to the fact that its development follows the lines of force of the solar magnetic field.

to assume that its movement adheres to both the laws of motion of fluids and the laws of motion of charged particles in a magnetic field. The science dealing with the dynamics of all these motions is called magnetohydrodynamics. This science was developed to resolve the problem of the motion of charged particles in magnetic fields, and especially to predict the trajectories of those electrons and protons emitted by the sun that reach the Earth. Recently, magnetohydrodynamics has resolved certain problems relative to the laboratory production of plasma at extremely high temperatures, and is also employed in answering complex questions concerning the motion of solar material.

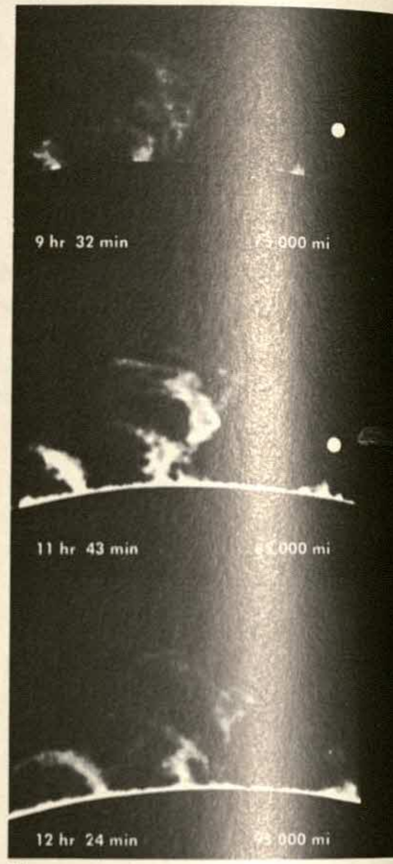
One odd fact that has been detected through observation of solar prominences is that conspicuous parts often cease and then resume their luminosity, keeping the same shape as before. A prominence may suddenly become luminous along its whole extent, or it may become progressively luminous almost as if it were catching fire; such luminosity spreads at great speed. This phenomenon is easily distinguishable from actual motion of the gaseous matter making up the prominence. In the latter case, the velocity of the material of the prominence is measured by the Doppler effect.

The movements of the prominences show a fascinating aspect of the sun's life, and photographs show the full extent of their beauty. Solar prominences are generally photographed with a motion picture camera attached to a telescope or to a coronograph, which registers a photograph every few seconds. A film of the entire duration of a prominence permits measurement of its velocity and plotting of its trajectory.

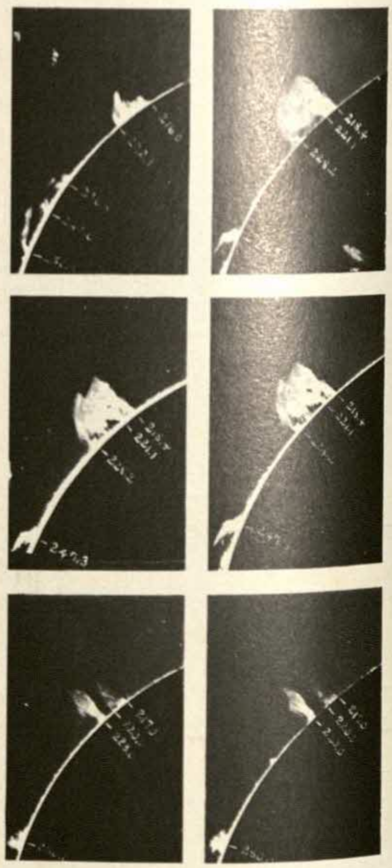
EMISSIONS FROM THE SUN

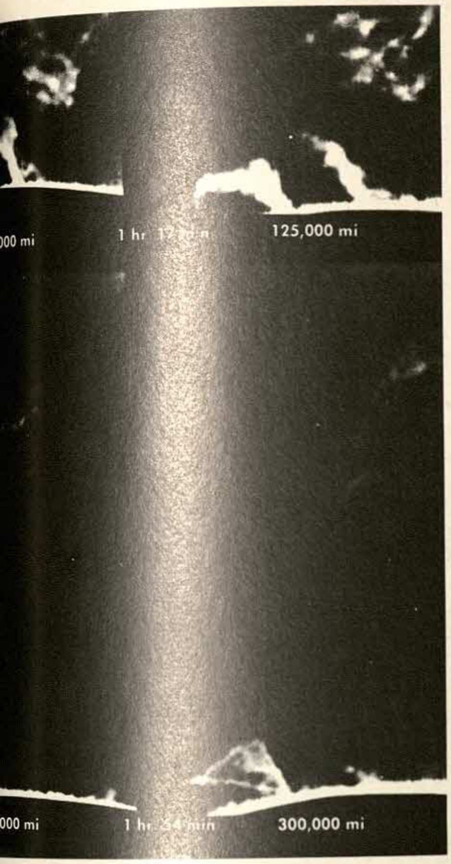
The sun's escape velocity is about 600 km (about 373 mi) per second. A particle of matter must move at least at this velocity

5a



5b





to escape the sun forever. The escape velocity of the sun is much greater than that of the Earth because the gravitational attraction of the sun is much greater than that of the Earth.

Solar prominences rarely reach escape velocity. At an altitude greater than the sun's radius above the photosphere, however, the sun's escape velocity is much lower. For this reason, the higher parts of prominences occasionally move away from the sun at velocities far exceeding their initial velocities. As a result, the matter making up the highest parts of these prominences escapes the sun's gravitational attraction and is dispersed into space.

The sun, however, emits material in other ways. Many phenomena of sudden activity, such as solar flares, are often accompanied by emissions of swarms of electrons, and sometimes of protons, both of which reach the Earth. The mechanism that moves these charged particles through space between sun and Earth is very different from that which moves the prominences. The particles are pushed by the pressure of solar radiation, or proceed through inertia, after having undergone mechanical thrusts from the underlying solar material. Particles issuing from the zones of solar activity are accelerated instead by electromagnetic phenomena. The rapid formation of a magnetic field can accelerate an electronically charged particle to a velocity close to that of light. Although it is clear that the mechanism of acceleration is based on this phenomenon, the details are not yet known.

Systematic observation of solar flares has shown that they are generally followed by magnetic disturbances in the Earth's atmosphere and by auroras. The time interval between these disturbances and the appearance of solar flares is determined by the type of solar flare, and depends on the velocity of the particles. The average velocity of the electrically charged particles that reach the Earth varies from thousands of kilometers per second to more than a hundred thousand kilometers per second. The arrival of electrons and protons affects the Earth's magnetic field so much as to cause the needle of a compass to deviate by many degrees. This effect is due to the passage of these charged particles near the Earth and not to the magnetic fields that are formed on the sun's surface. If the latter were true, the magnetic disturbances of the Earth's atmosphere would be detected at the instant of their formation and not after a delay that is sometimes more than a day. Lastly, the arrival on Earth of these swarms of particles produces an atmospheric luminescence known as the aurora, which occurs over both of the Earth's poles. The charged particles follow most easily the lines of force of the Earth's magnetic field; and these lines of force pull the particles toward the Earth's poles, where the lines of force of the Earth's magnetic field converge.

6

CORRELATION OF SOLAR PHENOMENA—In order to discover the link existing between phenomena that appear to be different, such as prominences, solar spots, flocculi, and solar flares, astronomers often combine photographs of the prominence with a spectroheliogram of the solar disk. This photographic combination of the solar events of August 14, 1907, discloses an obvious relationship between a prominence **a** and flocculi **b.**

ECLIPSES OF THE SUN | from objects of terror to objects of study

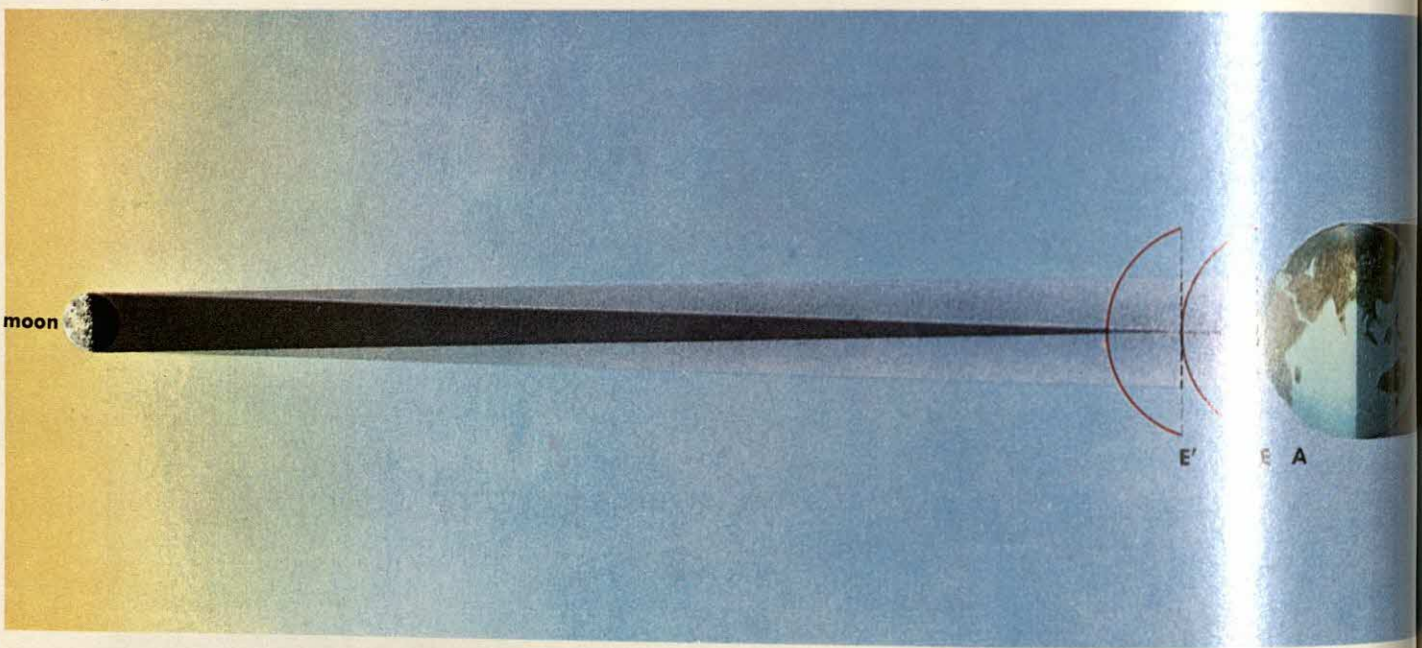
The total solar eclipse—with its abrupt transition from daylight to dusk to dark—is one of the most dramatic of all celestial spectacles. Because a solar eclipse is observable without the aid of a telescope, it has fascinated and awed mankind through the ages.

In ancient times, eclipses of the sun were viewed with terror. Primitive man believed that the darkness that suddenly blotted out the sun's life-giving light was an omen of the gods' displeasure. Among the many mentions of eclipses in ancient writings is an account by Herodotus, describing a battle between the Lydians and the Medes that ended in a sudden, fearful truce after a blotting out of the sun. Pindar, in a poetic message to Thebes in 463 B.C., pondered on the mystic portent of an eclipse: "Beam of the sun! O thou that seest afar, what wilt thou be devising? O mother of mine eyes! O star supreme, reft from us in the daytime! Why hast thou perplexed the power of man and the way of wisdom, by rushing forth on a darksome track?"

Solar eclipses did more than spark terror and awe in the ancient world. They inspired one of mankind's earliest investigations of the mysteries of nature. Long before Pindar's poetic musing, ancient scholars had studied and begun to chart eclipses. In China, where literature deal-

1

a



GEOMETRICAL CONDITIONS NECESSARY FOR A SOLAR ECLIPSE—An eclipse of the sun occurs when the moon, in its orbit around the Earth, comes between the Earth and the sun, casting a shadow over the face of the Earth. This shadow consists of two distinct parts—the umbra, or total shadow, into which no direct sunlight penetrates, and the penumbra, or half shadow, which is partially penetrated by direct sunlight.

By an exceptional coincidence, the sizes and distances of the sun and moon are such that each subtends very nearly the same one-half degree angle in relation to the Earth. However, their apparent sizes—as viewed from Earth—are not constant; they vary according to the pattern of the elliptical orbits of the Earth and moon. As a result, when Earth is at its nearest approach to the sun, and the moon is at its greatest distance from Earth, the apparent disk of the moon is far smaller than the sun. Conversely, when the distances are reversed the moon's disk appears larger than the sun. Thus, the totality, duration, and geographical sighting of a solar eclipse depend on the orbital positions of Earth and the moon at the time of the eclipse.

Illustration 1a shows the relative positions of the moon, the Earth, and the cone of the lunar umbra formed by solar illumination. With the moon moving around the Earth on an elliptical orbit, the full moon or new moon phases can occur when the moon is at apogee or perigee or in an intermediate position. Eclipses of the sun can also take place in any month of the year. Therefore, the apparent size of the sun in relation to the moon at the time of a solar eclipse depends on the time of the year and the distance separating the sun and Earth in its eliptical solar orbit. For example, the sun appears larger during the winter than in the summer.

When Earth is at point **A** in its orbit, the vertex of the lunar umbra cone falls short of the Earth's surface. When this occurs, the result is a partial, or annular, eclipse. (The phases of an annular eclipse are shown in Illustration 1b.) If the umbra's contact occurs when Earth is at orbit position **E**, the eclipse will be total at the vertex of the cone, but will last only a moment. (The stages of its development are shown in Illustration 1c.) Lastly, when umbra contact occurs while Earth is at orbit position **E**, the cone's vertex covers a much larger area of the Earth. At such times, not only is the area covered by the total eclipse far more extensive, but the blackout lasts much longer. (The stages of the development of a total eclipse are shown in Illustration 1d.)

Illustration 1b shows the phases that occur during an annular eclipse. The moon approaches the sun from the right and begins to cover it from Earth's view. This instant **1** marks the beginning of the eclipse. Continuing its movement, the moon progressively blankets the sun's disk. As the sun is covered, a moment is reached when the moon's disk, which appears smaller than that of the sun, is at an internal tangent to the easterly portion of the solar disk. This is the moment of second contact **2.** From this point on there is no further increase in the extent of covering until the moment of the third contact **3,** which occurs when the internal tangent of the moon is to the west. During this period of the maximum phase of an annular eclipse, the external portions of the luminous solar disk remain visible. Daylight is greatly diminished, but at no time does the eclipse become total. The sun's chromosphere, prominences, and corona are not visible, nor are any stars discernible. Annular eclipses provide little information of value. However, they can be useful in determining the moments of contact, and in checking the accuracy of lunar-solar chronometers. An annular eclipse ends when the moon moves away from the sun at a left, or easterly, tangent **4.**

When the vertex of the lunar umbra's cone barely reaches the Earth's surface, a brief total eclipse occurs (Illustration 1c). However, it is visible only from a small area of the Earth and lasts for only a split second. As a result, a total eclipse of this type is of little scientific value.

A total solar eclipse (Illustration 1d) is of longer duration and evolves in the same way as an annular eclipse. However, owing to the orbital positions of the Earth and moon, the moon's disk appears larger than that of the sun. Thus, to an observer within the range of the umbra during the second and third phases of contact the disk of the sun appears completely covered by the moon.

ing with eclipses dates back nearly 4,000 years, the first known scientific record of an eclipse was made by astronomers in 1217 B.C. Thereafter, Chinese, Chaldean, Greek, Babylonian, Assyrian, Roman, and Egyptian scholars chronologically recorded the sun's periodic blackouts. From such records, ancient scientists were able to determine both the intervals between eclipses and the relative motions of the sun and moon.

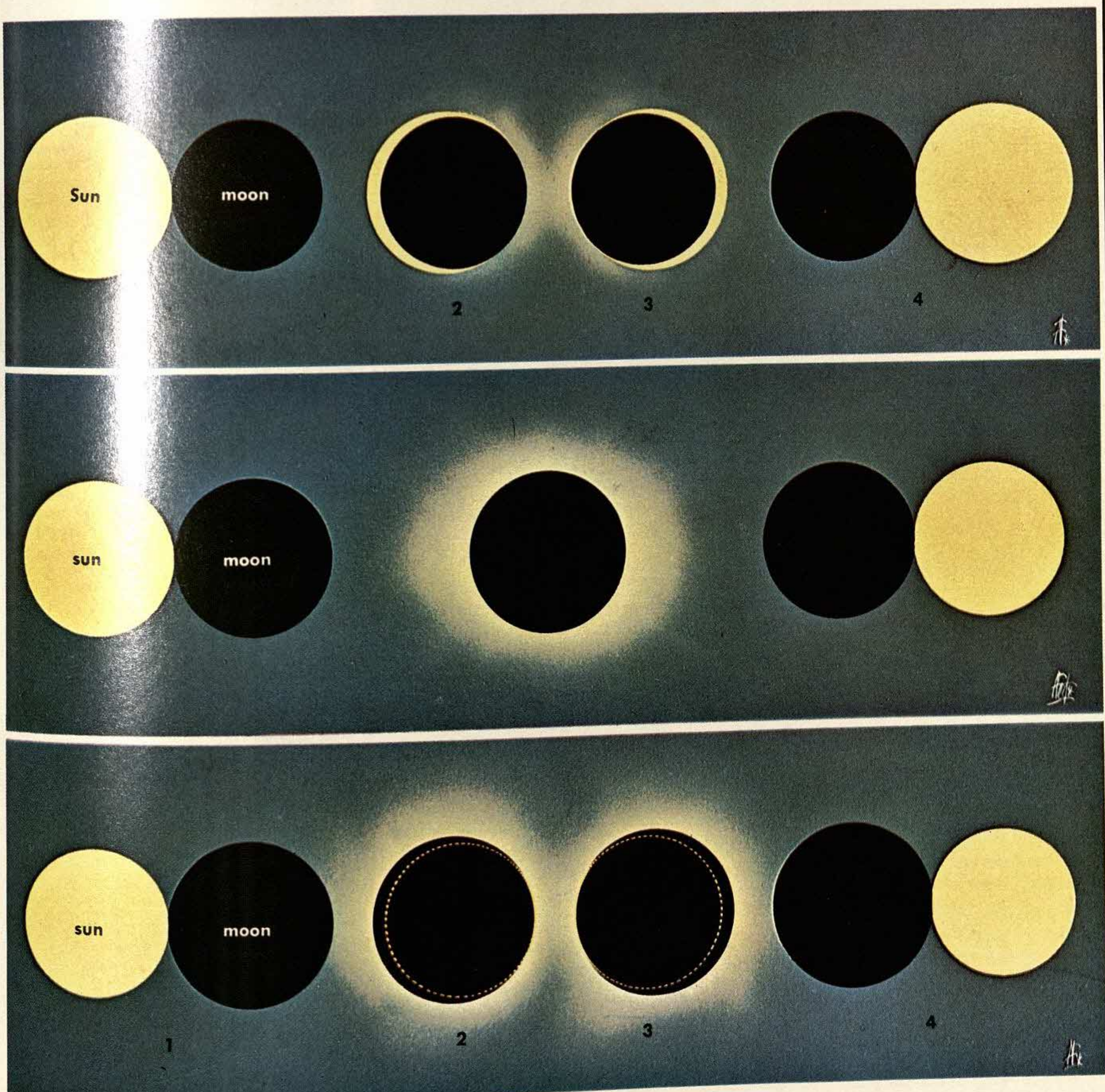
Although the ancients were eventually able to predict a darkening of the sun, they could not pinpoint a specific time, nor could they fully explain the cause of a solar eclipse. Many related it to an act of the gods rather than to a natural phenomenon. For example, in 168 B.C., during Rome's war with Macedonia, Roman soothsayers interpreted a solar eclipse as a portent that the king of Macedonia would fall.

Although deeply rooted in mythology, the eclipse records kept by scholars of the ancient civilizations provided a valuable basis for modern-day astronomical knowledge, especially in the determination of "secular accelerations"—the study of progressive changes in celestial motions. In 1749, for example, Richard Dunthorne used records of eclipses compiled over a 2,000-year period to demonstrate the existence of such celestial accelera-

b

c

d



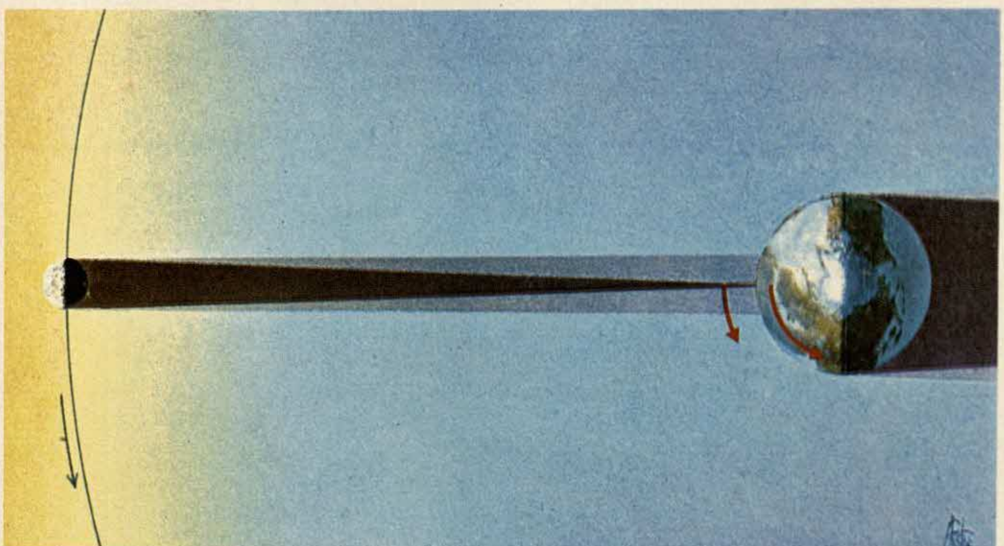
Inasmuch as the umbra cone is exceedingly narrow at the point of its intersection with the Earth, a total eclipse is confined to the narrow area over which the umbra passes. However, this narrow belt of totality may extend for thousands of miles across the Earth's surface. During the period of totality all direct sunlight vanishes; as the sky suddenly darkens, the brightest stars become visible, and the moon's dark disk appears to be framed by the pale halo of the sun's corona.

tion. In 1787, the French astronomer P. S. de La Place utilized ancient records as a basis for development of the first great text on celestial mechanics. Now, however, the factors which produce an eclipse are fully understood. With the rapid advances of computer technology during the last two decades, the various stages of the phenomenon have been calculated to within a fraction of a second several years in advance.

Today, many observations that were once conducted by astronomers only during a total solar eclipse—such as examining the external solar layers that are normally hidden by the sun's brilliant glare—are no longer dependent on an eclipse. Development of such instruments as the coronagraph has enabled astronomers to observe the sun's atmosphere, or chromosphere, on a clear day. Thus, the study of the sun's chromosphere, and of its corona and solar prominences, no longer must wait on total solar eclipses, which are relatively infrequent, often occur in distant parts of the world, and last only a few minutes.

Nevertheless, the natural phenomenon obviously is more dramatic than artificially produced effects. Also, certain phenomena can be studied only during a total eclipse; moreover, a total solar eclipse provides the opportunity to study solar radio effects and terrestrial ionospheric phenomena that normally cannot be detected because of the relatively small resolving power of radio telescopes.

2



THE DURATION OF A SOLAR ECLIPSE—The duration of a total solar eclipse—the time that passes between the second and third contact—depends on the latitude from which the eclipse is observed. As shown in this illustration, the moon's umbra moves over a portion of the Earth, traveling at approximately the same velocity as the moon in its orbit. The red arrows indicate the direction of movement of the umbra, which advances at approximately 3,300 km (about 2,050 mi) per hour. However, an observer on Earth will not see the umbra pass at this speed because the Earth is rotating in the same direction as the moon's shadow. The velocity of the Earth's rotation depends on the latitude. The maximum rotational velocity is about 1,700 km (about 1,056 mi) per hour at the equator, or nearly 50 percent slower than the speed of the umbra. At higher latitudes, the rotational velocity is lower, and the speed with which the umbra passes across these areas is greater than at the equator. Thus, the maximum duration of a total solar eclipse is 7 minutes, 40 seconds for a stationary viewer at the equator; at a latitude of 45°, the period of totality does not exceed 6 minutes, 30 seconds. The total duration of all phases of a total solar eclipse, from the first through fourth contacts, is approximately 4 hours.

3

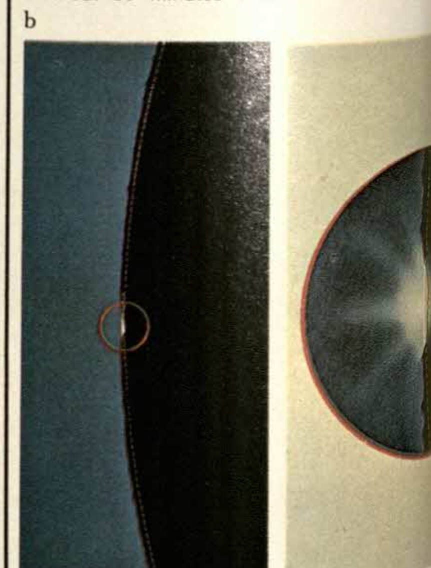
a

HOW A SOLAR ECLIPSE TAKES PLACE—There are no advance meteorological or climatic warnings of an approaching eclipse. The moment of first contact can be observed only with the aid of astronomical instruments, which enable the viewer to see the sun's blinding light in a suitably filtered way. An observer with the proper viewing instruments first becomes aware of a sudden indentation in the sun's luminous outline. This encroachment on the sun's disk seems to spread rapidly during the first moments. Although the speed of the widening eclipse then seems to diminish, this is an illusion, for the moon moves at a steady pace as its orbit takes it across the solar disk.

At the moment of first contact, astronomers determine if the advance eclipse time calculations were exact. Often the forecast is a fraction of a second off, and in exceptional cases even a second or more behind or ahead of the calculation. Such errors are not the result of mistakes in calculation, but are caused by incomplete knowledge of the perturbations that affect the motion of the moon.

About 30 minutes after first contact, the

b

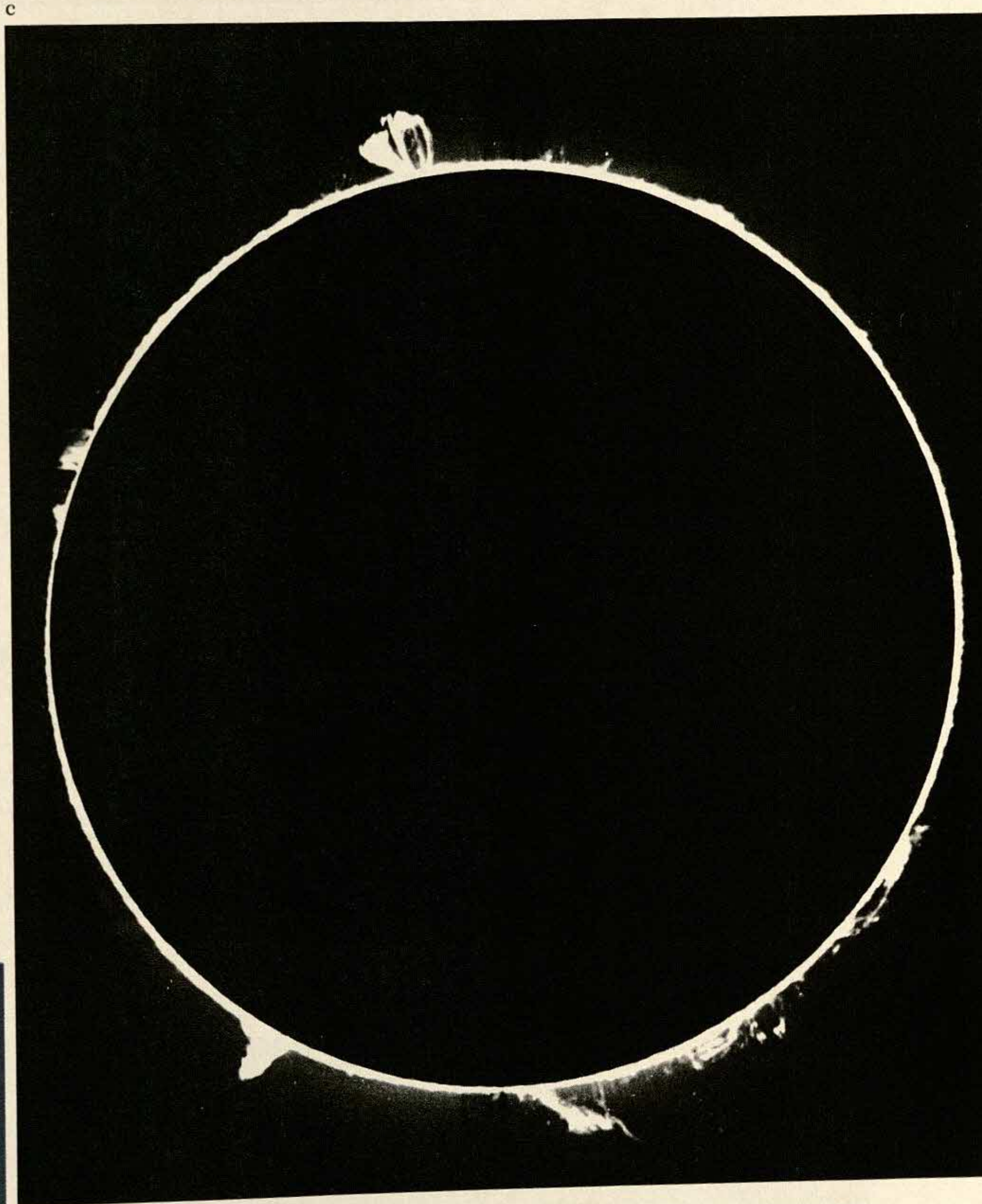


eclipse is easily observable. A solar eclipse should be observed only through a very dark smoked glass—much darker than that of ordinary sunglasses—or through four layers of heavily fogged film. Unless such precautions are taken, serious eye injury or blindness may result.

The approach of totality is accompanied by an ever-deepening dusk that evolves slowly enough—over a period of about 1¼ hours—to cause a lessening of solar radiation striking Earth, with a resultant decline in temperature. In the moments preceding totality, the diminution of light and temperature is so rapid that many animals become terrified, and birds frequently return to their nests to sleep. Often the thermal phenomenon is accompanied by an inversion in wind direction. In the final moments before the abrupt transition from dusk to darkness, the solar outline is etched with the reddish flares of the sun's chromosphere and prominences, adding an eerie, awesome beauty to the phenomenon (Illustration 3a). The onset of totality is also preceded by a brief interval in which the moon's disk almost covers the sun, leaving a thin rim of the solar surface still exposed and shining brightly (Illustration 3b).

In the first moments of the solar blackout, the darkest eclipsed area on the Earth seldom exceeds 10 km (about 6 mi). The sun's light, although greatly diminished, filters through the atmosphere from all sides of the horizon. However, the area of totality rapidly widens, sometimes to a path about 160 km (about 100 mi) wide. Along this path of totality, darkness is similar to a night illuminated by a full moon. With the moon blanketing all of the sun's brilliance except for the halo of the corona, the brightest stars become visible. During totality, the nature of the light that reaches the Earth is determined by phenomena that are developing on the sun. The corona's light is a violet gray, and predominates according to the sizes and intensities of solar prominences at the time of the eclipse. Illustration 3c is a photograph taken during a total eclipse occurring at a time of intense solar activity.

c



During totality, the weaker stars and the various phases of the corona can be photographed. Although the light of the corona easily registers on the film, its luminosity decreases by a factor of over 100 between the limb and the distance of one solar radius from the surface; furthermore, the corona is more than a million times fainter than the disk itself. Therefore, to obtain successive photographs of the corona, different exposure times must be used for the varying phases.

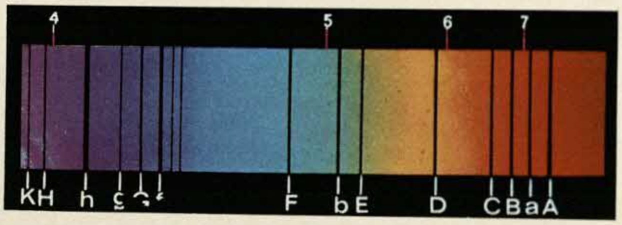
The third contact marks the end of totality. From this point on, sunlight begins to return, and the phenomena described above reoccur in reverse order. Daylight returns as suddenly as it vanished, and the thin crescent of the sun gradually expands. Approximately 1½ hours later, the second partial phase of the eclipse ends with the fourth contact, when the moon's final intrusion on the solar rim disappears.

THE SUN THROUGH ITS SPECTRUM | capturing the sun on film

Sir Isaac Newton discovered as early as 1666 that a beam of sunlight would produce all the colors of the rainbow when passed through a glass prism. Later scientists were able to interpret this rainbow of color, called a spectrum, as the components of ordinary white light. By means of spectral analysis certain facts about the physical and chemical composition of the sun and other stars have been determined.

THE SPECTRUM OF THE SUN—The dark lines are caused by elements in the sun's atmosphere, each of which absorbs light of one particular color. The letters indicate the most clearly marked lines discovered by Fraunhofer.

1



THE SPECTRUM OF THE PHOTOSPHERE

A telescope reveals the sun as a disk of intense brightness. Its dazzling surface, known as the photosphere, is an almost perfect sphere; it acts as a boundary between the inner part of the sun—where the atoms of the sun's main constituent, hydrogen, are ionized or missing their electrons—and the outer part, where the hydrogen atoms are whole. The ionized hydrogen lying beneath the photosphere has a temperature increasing from about 6,000°K (about 10,300°F) at the photosphere to millions of degrees at the center of the sun. When the white light of the photosphere is observed through a spectroscope, the spectrum is found to include the entire range of colors from red to violet.

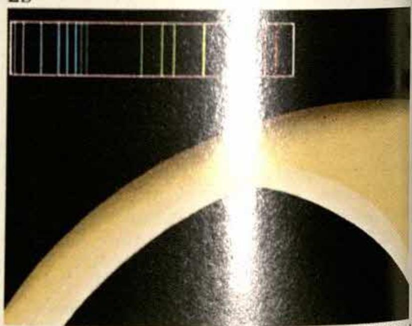
The spectrum of any substance may be studied by heating the substance until it becomes luminous. This process produces a mass of luminous radiation called an emission, or bright-line, spectrum. The emission spectrum can be recorded photographically as a collection of luminous lines. A second kind of spectrum appears to be practically the opposite; it is the absorption, or dark-line spectrum—so called because it appears as dark lines on a light background.

An efficient spectroscope will reveal a spectrum of the sun that includes a large number of these dark lines of varying intensity and breadth. These lines are Fraunhofer lines, named after Joseph von Fraunhofer, a German optical expert who discovered them in 1814. The clearest of these lines still carry the alphabetical designations used by Fraunhofer in his classification system. Illustration 1 shows the solar spectrum with its Fraunhofer lines. A small spectroscope for laboratory use in chemical analysis will show the solar spectrum as clearly as the illustration, but the most distinctive features of the spectrum can be seen only through an immense spectroscope used in an astronomical observatory.

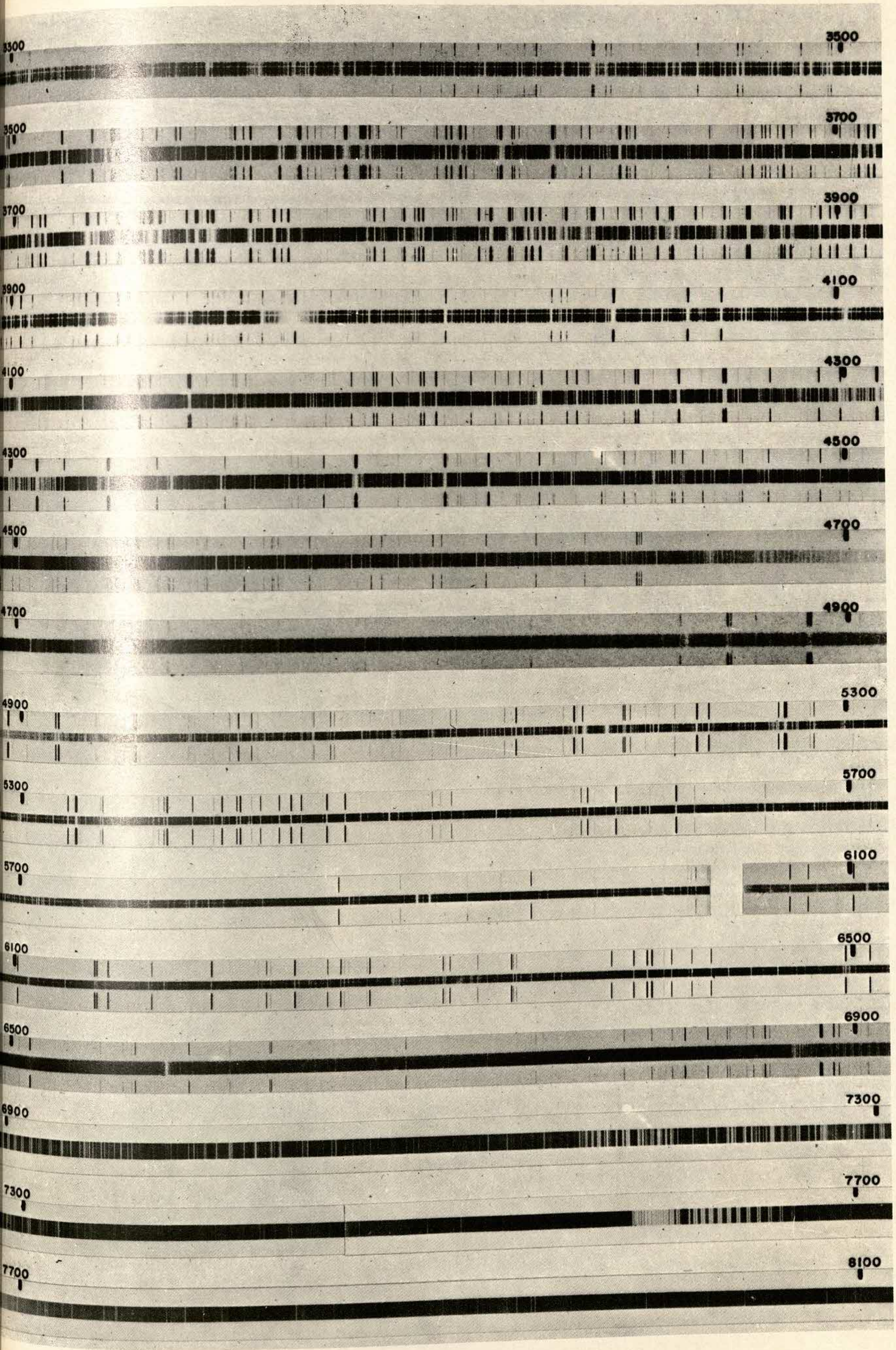
The Fraunhofer lines in the solar spec-

PHOTOSPHERE AND REVERSING LAYER—If the white light of the photosphere did not pass through layers of gas, the solar spectrum would appear as shown on the left (Illustration 2a), with no lines on it; an actual spectrum is shown on the right (Illustration 2a). The lines are dark on a light background. Without the body of the sun below it, the spectrum of the sun's gaseous atmosphere would show nothing but Fraunhofer lines. In this case the lines would be light on a dark background (Illustration 2b).

2b



2a



3

THE SPECTRUM OF THE SUN—A photograph of the complete solar spectrum would be 10 yards long and contain more than 20,000 absorption lines. Illustration 3 shows part of the spectrum for wavelengths from 3,300 to 8,100 Å.

trum are caused by a layer of gas, known as a reversing layer, that exists just outside of the photosphere. The density and temperature of this gas is lower than that of the photosphere. The gas is not ionized and does not allow all the light from the photosphere to pass through. It absorbs the colors that the spectrum shows are missing, and the Fraunhofer lines appear in their places. This is why the solar spectrum is called an absorption spectrum. To show the complete solar spectrum in all its detail would require a photograph 10 yards long. Such a photograph would contain more than 20,000 Fraunhofer lines.

The various elements present in the sun can be identified by comparing the spectra of known elements with the solar spectrum. This is done by superimposing the known-element spectra one by one on the solar spectrum, always using the same spectroscope. If the absorption lines coincide, the presence of that element in the sun is indicated.

The sun's spectrum contains lines for almost all elements. Those elements not indicated are among the rarest in the universe. The elements sometimes can be found in the sun and in other stars in more than one isotopic form. (Isotopes of an element have the same atomic number, but a different atomic weight.) A spectroscope can be used to study these isotopes because they produce lines almost identical to those of the basic element; the position of the spectrum of each isotope, however, is different.

EXTENDING THE SOLAR SPECTRUM

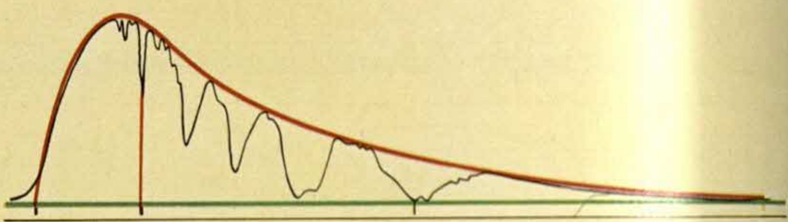
The sun's visible light and ultraviolet radiation down to about 3,000 Å (Angstroms) can be studied from photographs. (In spectroscopy, wavelengths usually are stated in Ångstroms. One Ångstrom is about 4×10^{-9} in., or one ten-billionth of a meter.) The sun produces other kinds of radiation, particularly infrared rays, which exceed 7,000 Å and ultraviolet rays with wavelengths of less than 3,000 Å. Ordinary film is useless in the analysis of the sun's infrared spectrum. This kind of analysis requires special film that is sensitive to infrared radiation. A further limitation on study of the infrared spectrum is the Earth's atmosphere, which contains both carbon dioxide and water vapor, both of which absorb some infrared radiation.

THE ULTRAVIOLET SPECTRUM OF THE SUN

The sun emits a considerable quantity of ultraviolet radiation having wavelengths below 2,900 Å; this amount would kill all living beings on Earth were the radiations not partly absorbed by the oxygen in the Earth's atmosphere. Even the small quantity of ultraviolet rays that reaches the Earth is strong enough to cause sunburn, and permanent damage can be inflicted on the retina of the eye if

4

INFRARED RADIATION EMITTED BY THE SUN—This graph represents infrared radiation emitted by the sun. Infrared radiation can only be perceived through its effect, which is to heat any body it strikes. Although the sun emits large quantities of infrared radiation, some of it never reaches the Earth because it is absorbed by the humidity and carbon dioxide in the Earth's atmosphere.



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X-RADIATION (X-RAYS) EMITTED BY THE SUN—This is how the sun would look to an observer if he could stand outside the Earth's atmosphere and if his eyes were sensitive to x-radiation rather than to visible light.

ultraviolet rays are absorbed continuously. More ultraviolet rays are present in mountain air because less oxygen exists at high altitude. For this reason scientists who wish to study ultraviolet rays send rockets to heights of 60 to 70 mi or incorporate instruments in man-made satellites.

The sun also emits a certain amount of x-radiation, which resembles visible light but has a much shorter wavelength. X-radiation is also blocked by the Earth's atmosphere. Photographs of the sun made by using x-rays as radiation (Illustration 5) show it as it would appear to human eyes sensitive to x-rays rather than to visible light.

Because lines from the photosphere pass through the various layers of Earth's atmosphere, the solar spectrum contains additional lines called telluric (meaning *earth*) lines. These may be distinguished from solar lines in several ways. Telluric lines, for example, vary in intensity according to the sun's height above the horizon. At midday the layer of air through which sunlight must pass is thinner than it is at dawn or dusk. One of the clearest of the telluric lines is produced by oxygen.

According to mathematical models of the structure of the sun, the temperature at the center is about 20,000,000° K. Going out from the center of the sun toward the surface, about 4,200° K is reached at the very top of the photosphere. In the chromosphere, the temperature begins to rise until the beginning of the corona, where the temperature is about 500,000° K. In the outer parts of the corona, radio observations are best fitted by a temperature of 1,500,000° K.

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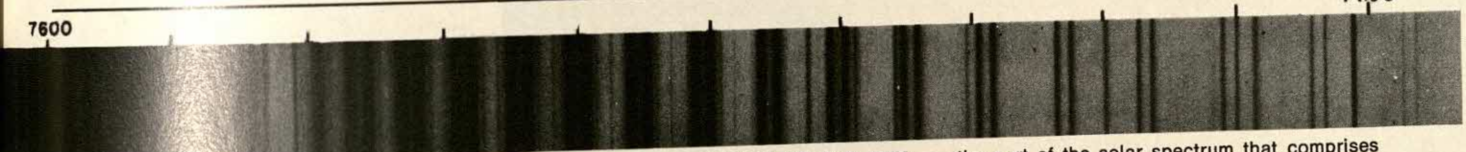
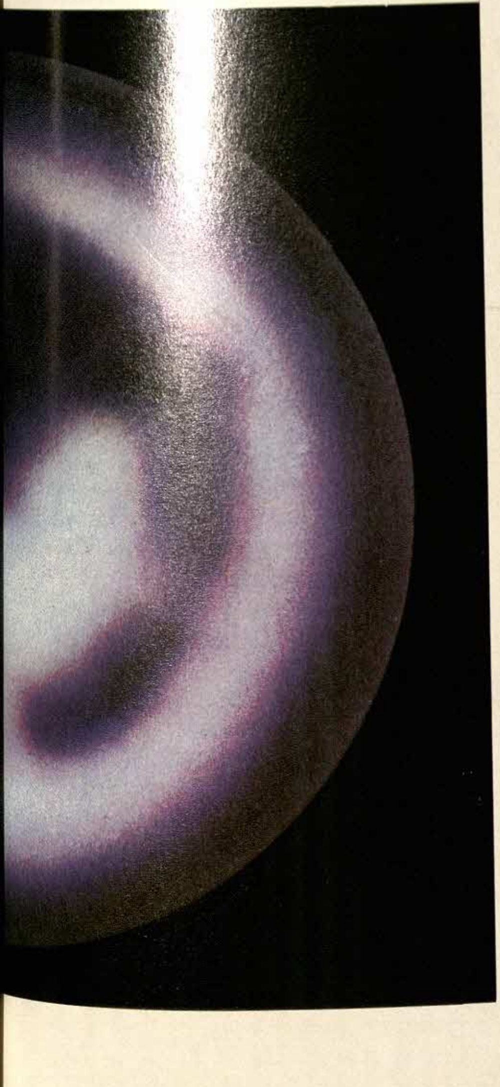


THE INFRARED SPECTRUM OF THE SUN— This photograph shows the infrared zone in the part of the solar spectrum that comprises wavelengths between 7,600 and 7,700 Å.



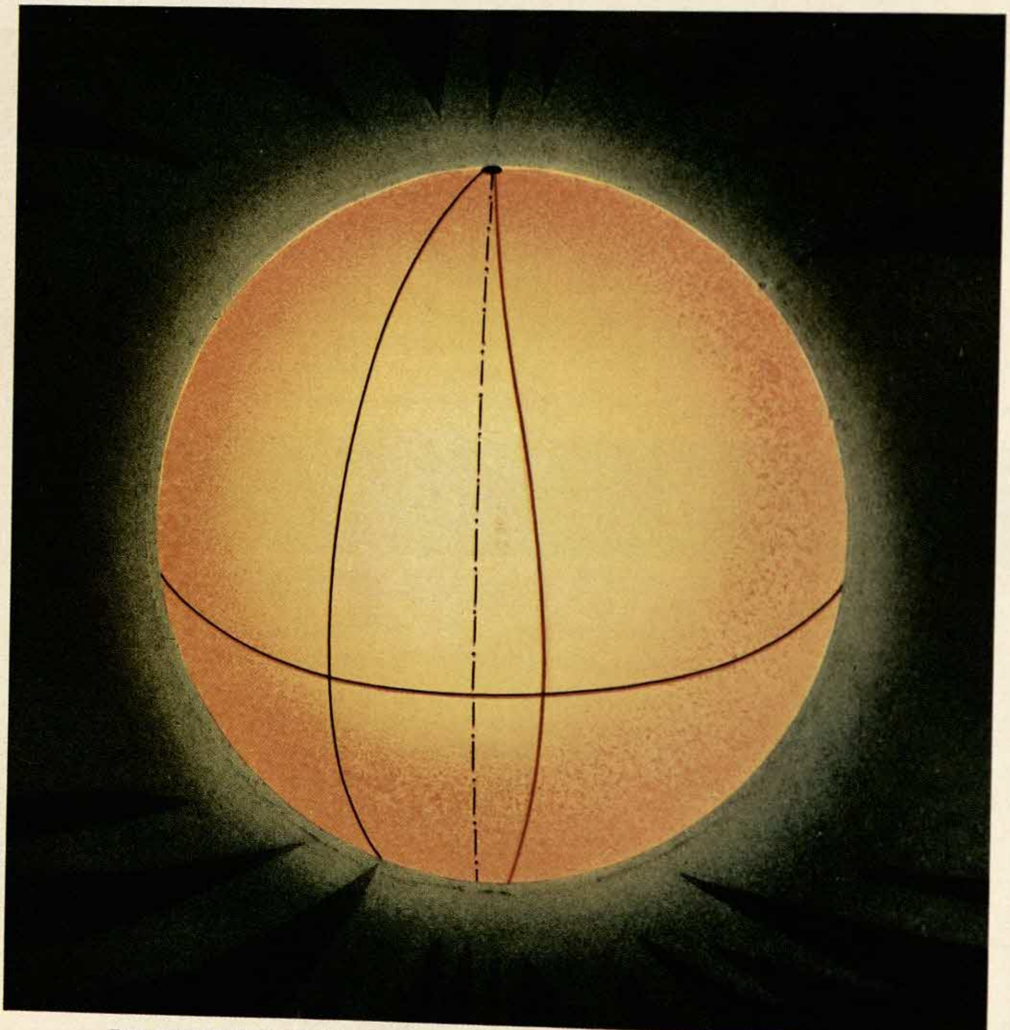
THE TEMPERATURE OF THE SUN

An instrument called a bolometer provides scientists with one way to determine the sun's temperature. A bolometer measures the amount of solar energy carried by each kind of radiation. In this way, the temperature of the photosphere has been estimated at 5,770° K (about 9,900° F). The absorption lines of the solar spectrum are formed mainly inside the reversing layer, just above the photosphere. Because the temperature of a gas determines the breadth of the spectral lines, the lines can be used to measure the temperature of the various layers of the sun's atmosphere above the reversing layer. Careful measurements reveal that these temperatures often exceed 6,000° K (about 10,300° F).

HARNESSING SOLAR ENERGY

Solar radiation at the outer limit of the Earth's atmosphere has an average intensity of 1.41 km per sq m (445 BTU per hour per sq ft), known as the solar constant. Only about 46 percent of the incoming solar energy actually reaches the Earth's surface, however; about 35 percent is reflected back into space by clouds, and the atmosphere absorbs the rest. For many centuries, man has tried to harness the sun's radiant energy. Advances have been made in using solar energy to generate heat, to bring about chemical reactions, and to produce electricity. Terrestrial solar-power systems have had little success because of the irregularity of operation and the excessive cost; but in space, the supply is certain and there are no competitive sources of endless energy. Artificial satellites and space vehicles employ thousands of silicon cells that pick up energy from the sun and generate power. The major potential areas for use of solar energy on land lie where sunshine is plentiful and other energy sources are scarce.

7



THE ROTATIONAL SPEED OF THE SUN—The sun is not a rigid body. Its speed of angular rotation is greater at the equator than at the poles. A point on the equator completes a full rotation in less time than a point near the poles. Points that start in line with each other on the same meridian (for example, the one on the left) will be out of line later, the points on the equator having moved ahead of those at the poles (as shown by the red line on the right). If the speed of angular rotation were uniform, the points still would be in line (as shown by the dotted line).

TURBULENT GAS IN THE PHOTOSPHERE AND THE REVERSING LAYER

When one of the narrower lines of the solar spectrum is examined through a large spectroscope, the edges of the line seem to be jagged. As time passes, the shape of the jaggedness changes; this change is caused by the movement of the sun's gas. Such movement is continuous and rapid because the surface of the photosphere is the place where solar energy, after struggling to escape from the center of the sun, bursts into space.

By a process of convection, the surface of the photosphere receives heat from inside the sun and radiates it into space. In much the same way that the surface of a liquid bubbles when heated from below, the solar gas in the reversing layer is churned by movements that cause it to rise and fall at a speed of several hundred yards a second.

When the reversing layer absorbs the light of the photosphere, it does not absorb the exact wavelength of light corresponding to each element because of the Doppler effect—the shifting wavelength of a star's light as it moves toward or away from the Earth. Slightly longer wavelengths are absorbed where the gas of the reversing layer is receding, while slightly shorter wavelengths are absorbed when it is approaching. As a result, parts of the spectral line seem to shift haphazardly either toward the red (longer wavelengths) or the violet (shorter wavelengths), thus causing the jagged edges of the line.

THE DIFFERENTIAL ROTATION OF THE SUN

Of the auxiliary instruments used with the telescope for investigating the sun, the spectroscope is the most important because it can select minute portions of the flood of radiation for special study. With a spectroscope, a scientist can cause the light from one edge of the sun to fall on one half of the slit through which rays pass into the instrument, and light from the other edge to fall on the other half. Because of the sun's rotation, the eastern edge approaches and the western edge recedes. The lines of the spectrum of the two edges shift position (because of the Doppler effect), and the extent of this shift reveals the sun's rotational speed. Measurement of this speed by observations at various latitudes of the sun's sphere shows that the sun does not rotate as a rigid body. Any point on the sun's equator makes a complete rotation in less time than does a point near the poles. This phenomenon also can be observed by measuring the time taken by the spots appearing on the sun's surface, the faculae, at various latitudes to complete one full turn. Illustration 7 shows how the equator's greater rotational speed causes a point on the equator to overtake those near the poles after a few rotations. Near the equator, the mean rotation period is 24.65 days; at solar latitude 20°, it is 25.19 days; at 35°, 26.63 days; and at 60°, 30.93 days.

THE EMISSION OF RADIO WAVES BY THE SUN | a natural transmitting station

Ever since the first radio-astronomical researches were undertaken, it has been apparent that radio waves are being emitted by the sun. The intensity of solar radiation did not seem very great at first. Radio telescopes could pick up solar radiation easily, but it was no stronger than interstellar radio sources. In fact, however, there are sources of radio waves within the galactic system that are equal in intensity to the waves emitted by the sun, indicating that their power of emission is infinitely greater. If the sun were ten million times nearer than these distant galactic sources, it would mean that their intensity is $(10^7)^2$ times that of the sun. The sun's radio waves, though not particularly intense, nevertheless, because of the sun's relative closeness to the Earth, can be studied in great detail.

EMISSION OF RADIO WAVES BY THE SUN

Transmission from a distant radio station is sometimes interrupted by irregular noises that vary rapidly in intensity. Solar radio emission, as well as emission from other celestial bodies, is basically similar, even though the origin of the two types of radio waves—terrestrial and solar—is different. Broadcasting disturbances can originate either in the Earth's atmosphere, where they are caused by electrical discharges, or in the solar corona.

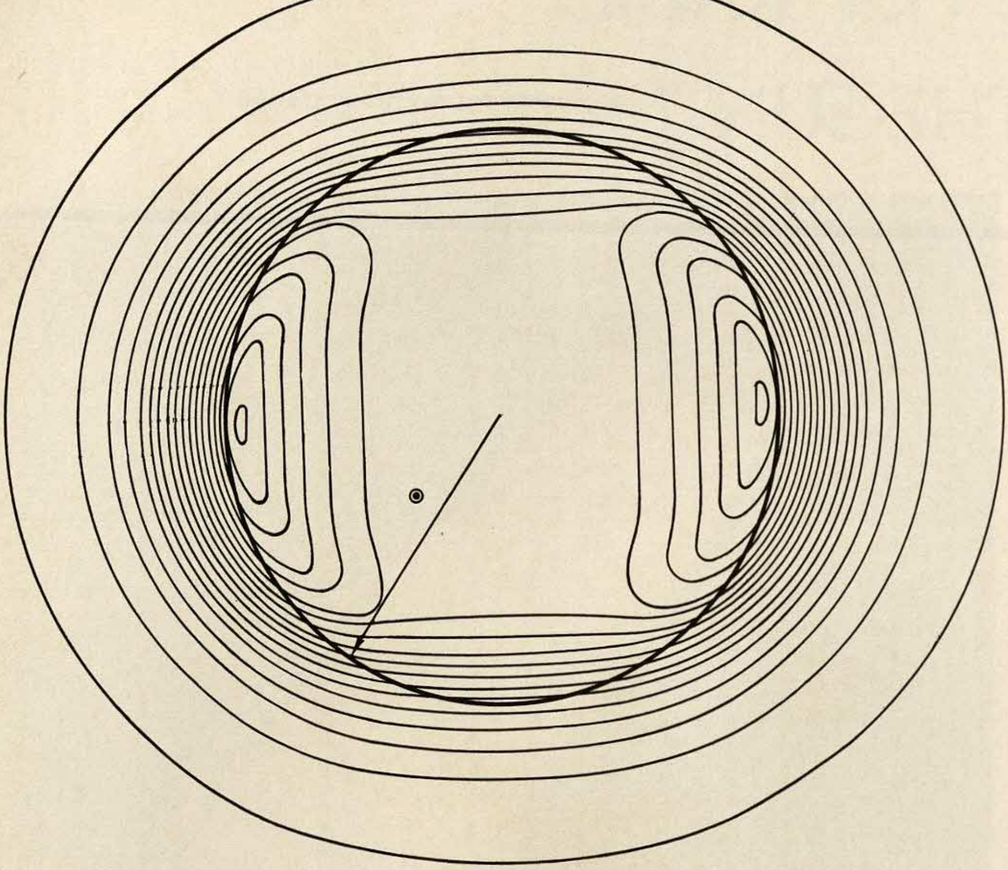
When an unknown radio source is studied, the most important thing is to determine the nature of the radio waves received, with the aim of understanding what could have produced them, and the physical makeup of the emitting source. Radio sources outside the planetary system generally are constant in their emission. The sun, however, does not always maintain the same intensity of emission. Because of this, it is customary to distinguish between the radiation emitted during long periods of weak radioactivity and the very intense radiation, emitted sporadically in conjunction with periods of strong solar activity, that is observable even with the eye.

It is, therefore, extremely interesting to correlate the sun's radioactivity with

1

A SOLAR RADIO TELESCOPE—Although the sun is a weak source of radio waves, it is possible to carry out studies of solar radiation without using complex instrumentation because the sun is relatively close to Earth. This radio telescope employs a dish antenna.

2a



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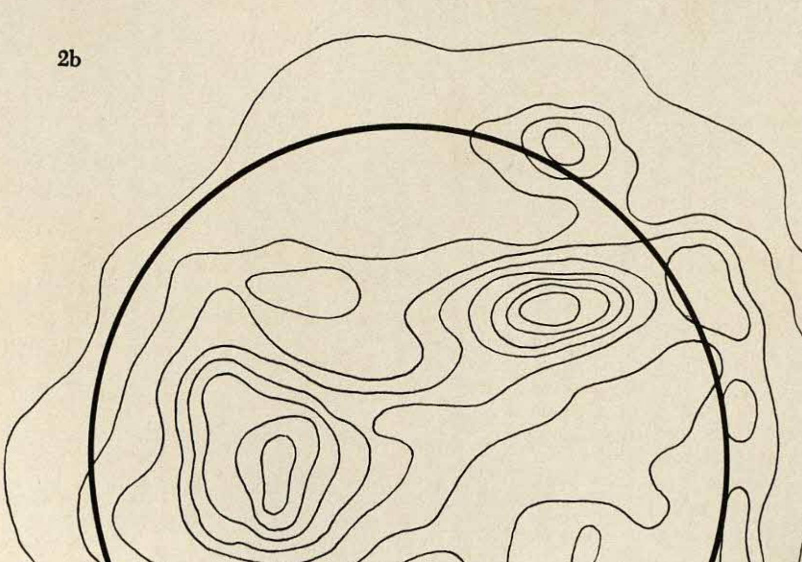

its visible activity. Because of this, astronomers constantly monitor the sun's radio waves with radio telescopes while simultaneously observing the solar surface.

INSTRUMENTS NECESSARY FOR THE STUDY OF SOLAR RADIO EMISSION

To receive and analyze radio waves from the sun, the same instruments are used as for studying more distant radio sources. Because of the relative closeness of the sun to the Earth, however, it is not necessary to use highly sensitive instruments.

The antenna, or energy collector, is the largest part of a radio telescope. Basically, there are two types of radio telescope antenna—the dish and the dipole array. The dish antenna is constructed of sheet metal or wire mesh, forming a large, shallow, parabolic mirror. The sheet metal or wire mesh collects radio energy and focuses it on a small antenna, operating under the same principle as the parabolic mirror, which collects light on the lens of a reflecting telescope. A dipole array is made up of many identical, rodlike antennas. These antennas collect strong energy patterns by feeding their weak individual signals into a single

DISTRIBUTION OF RADIO EMISSION ON THE DISK—If the entire surface of the solar disk is explored in a search for the distribution of radio emission, curves of equal intensity can be projected. These curves are spread out over the disk symmetrically if the sun is in a relatively inactive stage (Illustration 2a). The arrow indicates the radius of the visible sun while the dot inside a small circle indicates the power of resolution of the radio telescope's antenna. On the other hand, if the sun is active, the regular pattern appears completely altered (Illustration 2b). Above the centers of activity some regions that produce a much more intense emission appear.

When examined together with a photograph of the photosphere, it is evident that these centers of activity are near the focal points of visible disturbance. However, they do not always coincide. In fact, the bright patches in the photosphere are always connected with centers of radio emission, as shown in Illustrations 2a and 2b. The relationship is not direct, however, as can be seen from the fact that the center of radioactivity is almost always somewhat away from the center of visible turbulences. Proofs exist of the relationship between the two, primarily because they both emerge at the same time. A careful examination of radio emission data, however, shows that the center of emission is nearly always above the visible center, at a height that can be very great—a considerable fraction of the solar radius, for instance. Because of this, radio emission centers always appear to be removed from visible centers unless they are exactly in the center of the solar disk.

receiving set. The signals thus received by either the dish or dipole array are then recorded and analyzed by a variety of instruments. Antennas with extremely large parabolic reflectors are not required for studying the sun. However, the instruments necessary for analyzing the different wavelengths of the sun's radiations—ranging from a few millimeters to many meters—are highly complex.

When the radio emission from the sun is analyzed, astronomers search for the points on the sun's surface that are the sources of the radiation. Special instruments are necessary for this. When receivers with a single antenna and a parabolic reflector are used for observation, the possibility of picking out the direc-

THE APPEARANCE OF THE SUN AT DIFFERENT WAVELENGTHS—At a wavelength of 8.5 mm (about 0.3 in.), the sun's appearance does not differ much from that of the visible disk. The solar disk appears only a little larger and is surrounded by a border from which a more intense radiation is emitted. This border is increasingly accentuated at wavelengths of 3, 7, 10, and 20 cm (about 1, 2.75, 4, and 8 in.). At greater wavelengths, the sun appears larger, as a single, large emitting ring with a strongly shaded outline. Finally, at wavelengths greater than 2 m (about 6.5 ft), the sun is seen as a circular patch with shaded edges. The patch has a diameter equal to about three times the visible diameter of the sun. Thus, it follows that the solar radio emission comes from different levels of the corona—the shorter the wavelength, the lower the level.

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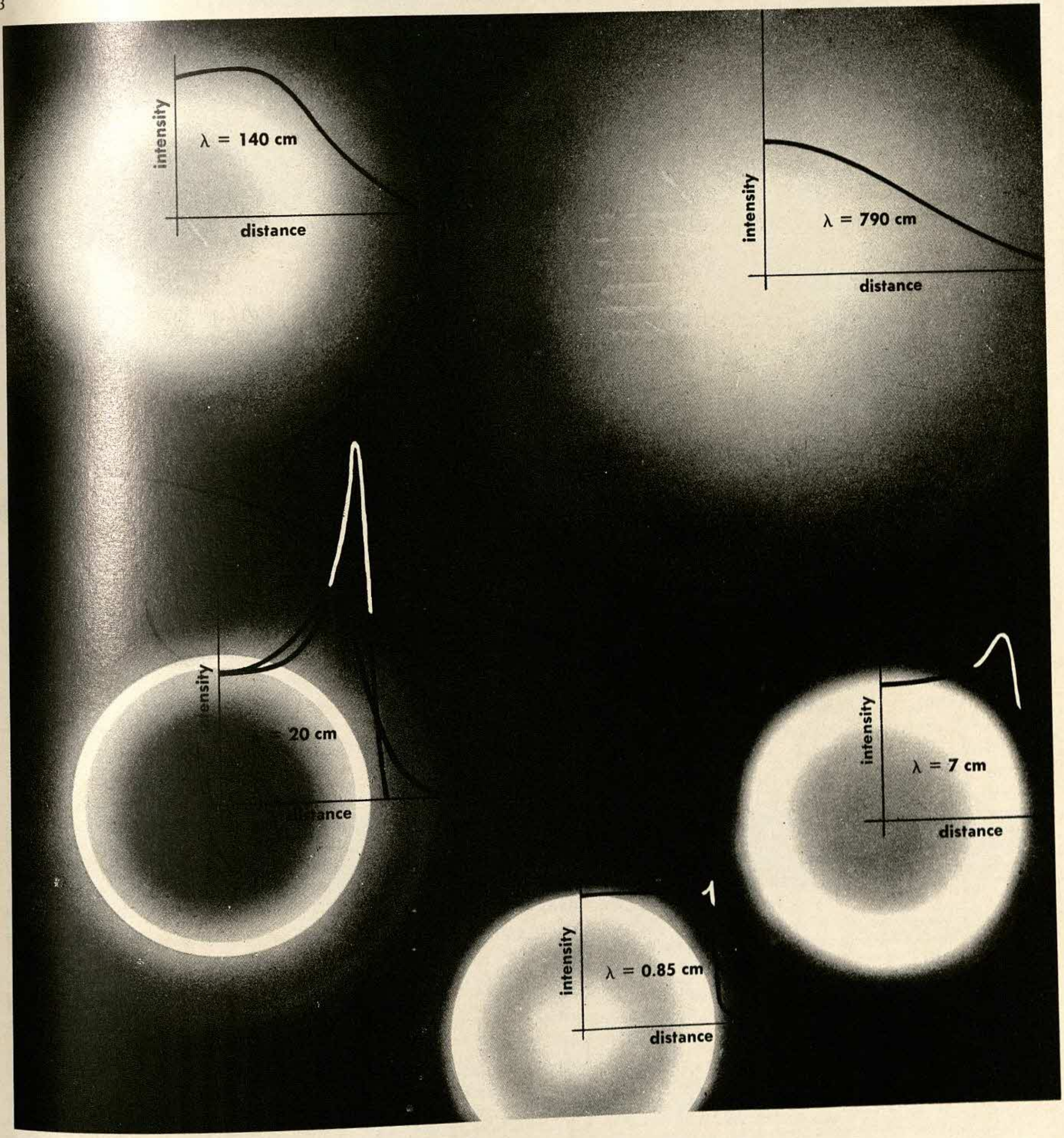

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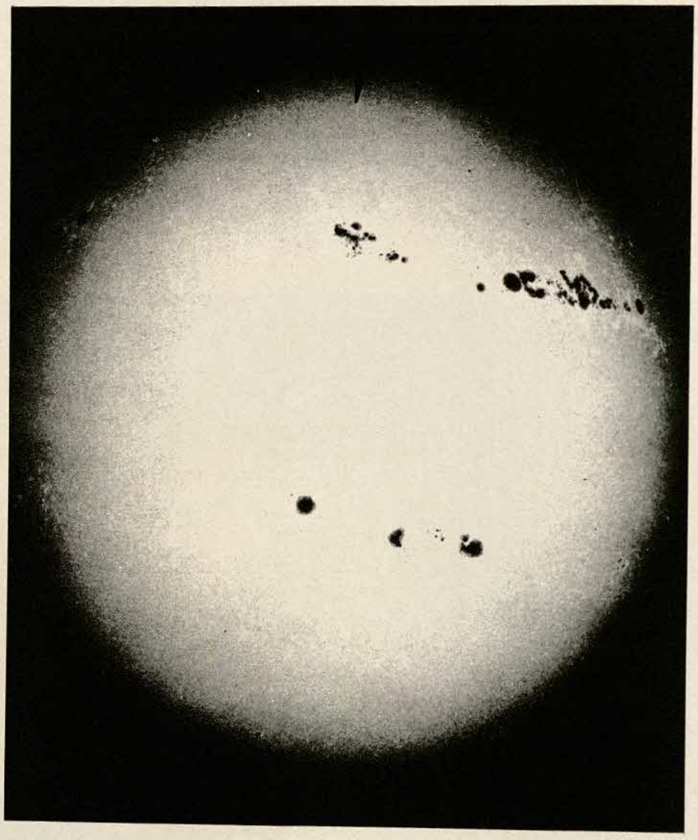
EMISSION WHEN THE SUN IS DISTURBED—Illustration 4 shows the sun when it is disturbed, with many spots distributed typically in two bands to the north and south of the equator. While the disturbances that are visible optically are localized on the bright solar surface, radio disturbances originate from much higher up.



tion of origin of the radio waves depends on the diameter of the parabolic reflector and on the wavelength of the radiation. More precisely, the power of resolution is directly proportional to the diameter of the parabolic reflector and inversely proportional to the wavelength. For reflectors with a diameter of several meters and radio waves of the same order of size, the power of resolution is slight. It is then difficult to localize the point on the solar surface that is the source of radiation. In this case, interferometers can be used—that is, lines of antennas, each of which receives the signal one after the other with only an infinitesimal delay. By a comparison of these signals it is possible to calculate, with great precision, the direction from which the radio waves come.

THE MECHANISM OF EMISSION

Solar radio emission is confined almost exclusively to the corona. The gas that makes up the corona is largely hydrogen and is almost completely ionized by the extremely high temperature. This temperature, which can exceed a million degrees, is caused by the fact that the gas in the solar corona can absorb energy from the underlying photosphere easily, while it can irradiate such energy only with difficulty. As a result, there are many free electrons present that are disturbed by strong thermal agitation. These electrons collide with the gaseous ions present in the same gas. As a result of these collisions, the velocity of the electrons varies sharply. Since an accelerated electric charge emits electromagnetic radiation, the electrons accelerated by the collisions emit an electromagnetic radiation whose wavelength depends on the mechanical characteristics of each individual collision. Therefore, according to the greater or lesser frequency of collisions of different types, x-rays, ultraviolet rays, visible light, infrared rays, and radio waves are produced from the solar corona. Since the electron collisions are completely random, radio waves of all lengths, ranging from a few millimeters to many hundreds of meters, are produced in solar emission.

The same factors that cause emission of radio waves in the corona also favor the absorption of them. The corona, in fact, contains free electrons that are able to vibrate in the electromagnetic field produced by transmission of a radio wave. The radio wave is thus absorbed, transforming its energy into the mechanical energy of an accelerated electron.

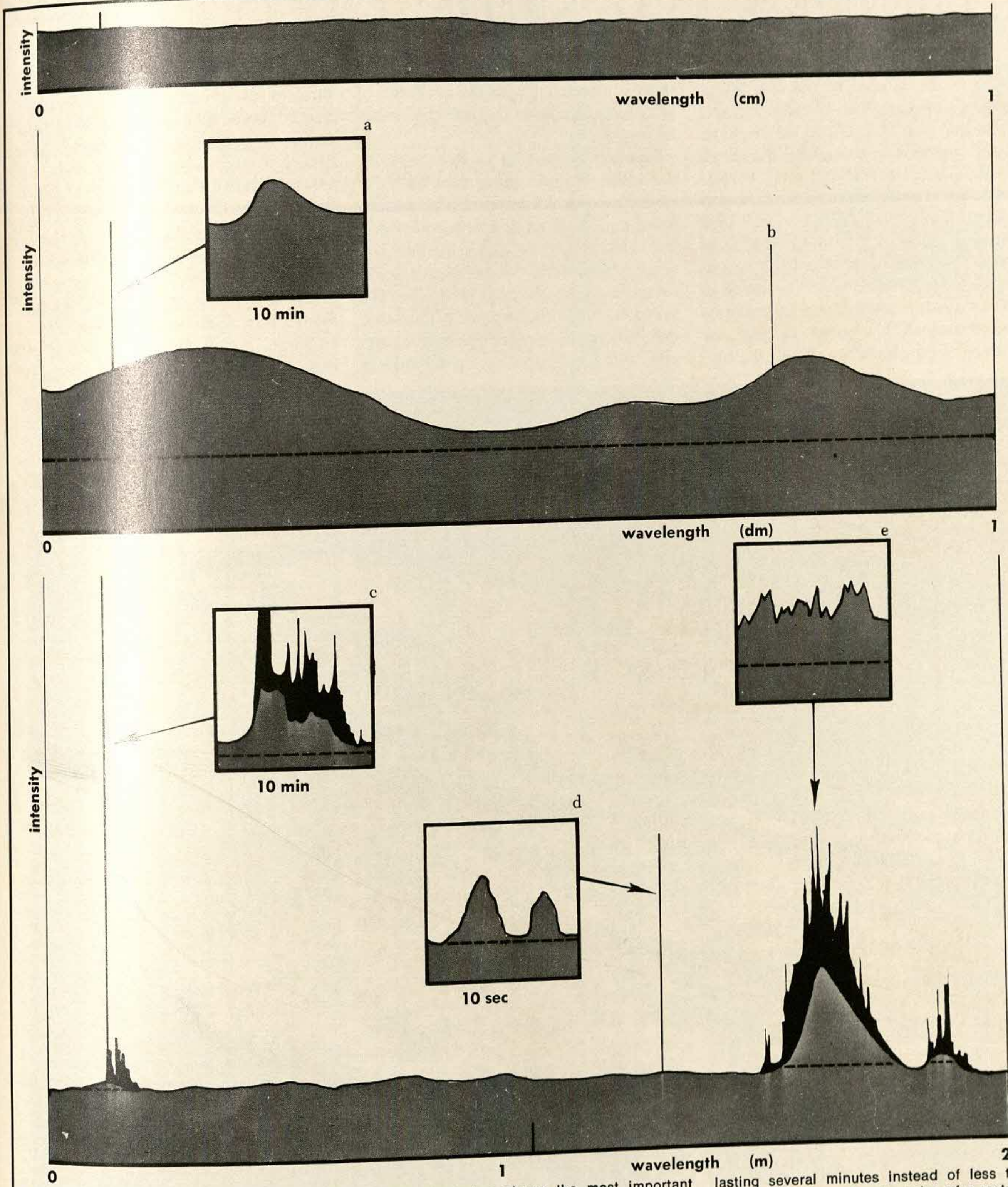
HOW THE ABSORPTION OF THE CHROMOSPHERE IS STUDIED

The sun periodically obscures many celestial bodies from the earth, among them certain extraplanetary radio sources. One of these sources is the Crab nebula in the constellation of Taurus. The radio waves emitted by this nebula are very strong until the sun slowly passes in front of it. The progress of the weakening radio waves indicates the increase of absorption owing to the sun. It is interesting to note that the obscuring of the distant radio source begins long before it is covered by the solar disk. This indicates that the sun is surrounded by a cloud of free electrons like those of the corona. The longer the radio wave the greater the absorption. Since energy absorption is accompanied by energy emission, it is obvious that the sun, as a radio emitter, is more powerful in the long, rather than the short, wavelengths.

HOW DIFFERENT WAVELENGTHS AFFECT THE RADIO IMAGE OF THE SUN

If the sun is observed through a gray filter, a disk more or less uniformly bright, with the edges a little darker, is seen. If the sun is observed through a red filter, the viewer sees a weaker darkening along the edges. However, if it is observed through a violet filter, the darkening is more accentuated.

A radio telescope reveals an analogous phenomenon, but surprisingly the radio emissions also exist outside the visible disk of the sun. The solar corona is responsible for most of the sun's radio emission. If an observer, therefore, could see radio waves instead of visible light, the sun would seem much larger. If the observer were able to see wavelengths of a few meters, the sun would appear at least three times larger. If he could see centimeter wavelengths, the limit of the sun would appear brighter than the center of the disk.



RADIO EMISSION WHEN THE SUN IS DISTURBED AND ACTIVE—The sun is continuously emitting a certain quantity of radio waves that serve as a background against which sudden, shorter, and more intense emissions take place.

This background component is quite constant. However, it shows a slight variation synchronized with the eleven-year cycle of emission activity. Among the occasional emissions that are superimposed on it, some are more intense for certain wavelengths—for example, for wavelengths of a few centimeters—while others produce wavelengths of several meters.

The illustration shows the most important disturbances emitted by the sun at various wavelengths in a period of time well removed from a period of activity. Shown in Illustration 5a is a fluctuation in intensity of background radiation. The cycle of this variation is about 27 days—that is, equal to the period of the synodic rotation of the sun. This variation is only appreciable at wavelengths over 1 dm (decimeter) (about 4 in.). Illustration 5b shows peaks of intense radio emission—that is, isolated, intense increases, but of brief duration (less than a second)—centered around metrical wavelengths. Illustration 5c shows disturbances similar to the preceding ones but lasting several minutes instead of less than a second. Storms of radio noise of a metrical wavelength are shown in Illustration 5d. Duration of the peaks may be less than a second, or many hours, or even whole days. Illustration 5e shows the highlighting of the background level after similar disturbances.

In general, when the sun is active, it emits with much greater intensity than normal for long periods, even days. Although these phenomena of emission are secondary, reflecting the general activity of the sun, their study reveals much about the behavior and origin of the solar atmosphere and corona.

THE SUN'S MAGNETIC FIELD | the eleven-year sunspot cycle

Deep in the interior of the sun, where temperatures approach 40 million° F and pressures near 1.3 billion atmospheres occur, physical processes unknown on Earth take place. The effects of these processes are observable only when they interact with the material of the solar surface. One of the most fascinating of these processess—and one least understood—is the generation and evolution of solar magnetic fields. These fields can be studied when they break through the surface of the sun. The cycle of the sunspots is associated with the evolution of solar magnetic fields and the sun's magnetic cycle.

Sunspots—appearing as dark spots in the solar surface—grow and fade in strength every eleven years. This pattern is but a phase of a twenty-two-year cycle in which the sun's magnetic field reverses itself, with the north and south magnetic poles shifting positions. The sunspots, 500 to 50,000 miles in diameter, generally travel in pairs, one in front and one behind, and most have a life-span of three to four months. The origin and action of sunspots has long puzzled astronomers. In recent years, however, a new branch of physics—magnetohydrodynamics—has led scientists to believe that sunspots are the products of magnetic fields breaking through the sun's photosphere.

A visual inspection of the flocculi—the extensive luminous clouds around a group of sunspots—can only suggest the existence of these magnetic fields. When an atom, which emits certain spectral lines, is found immersed in a magnetic

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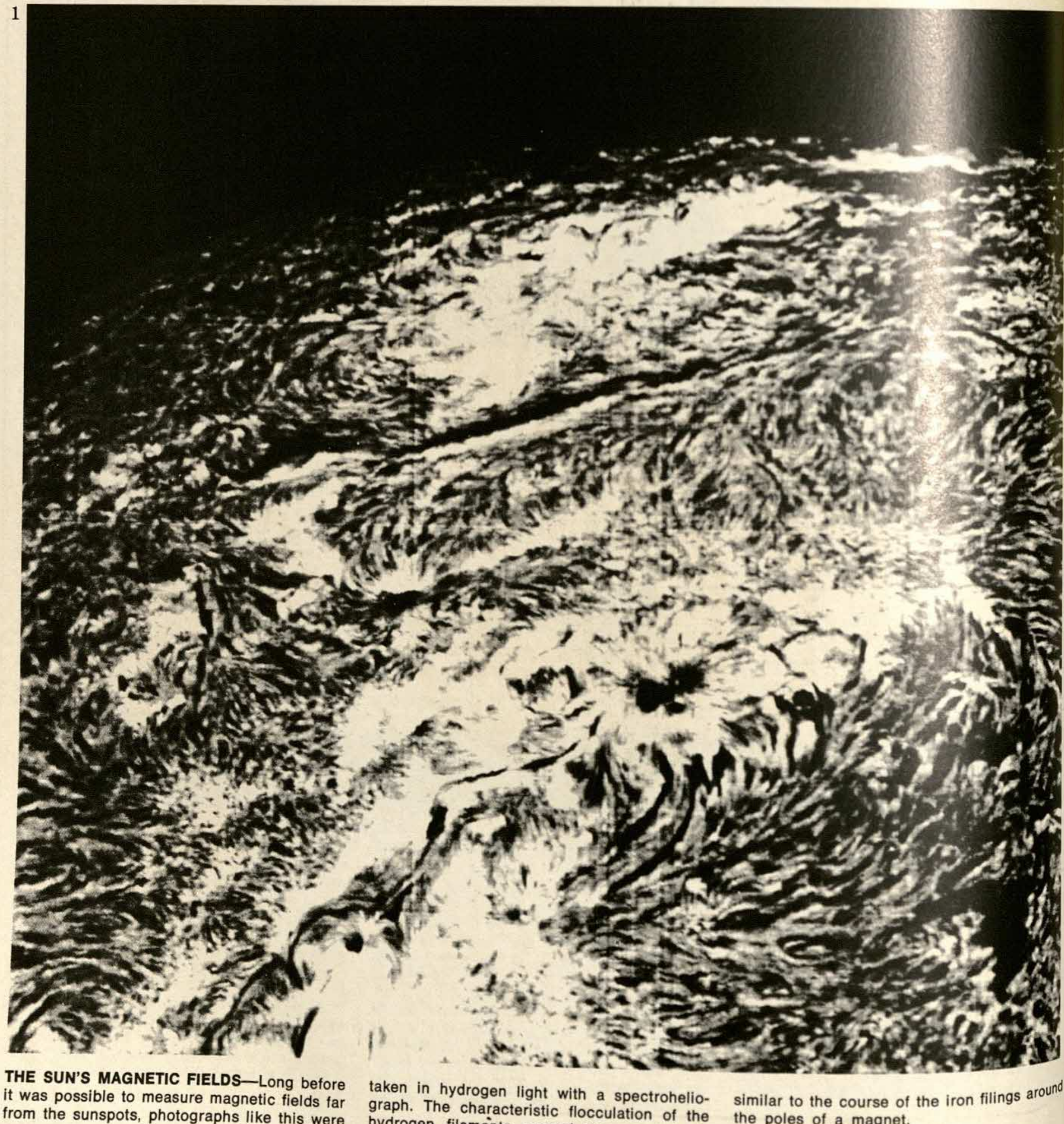
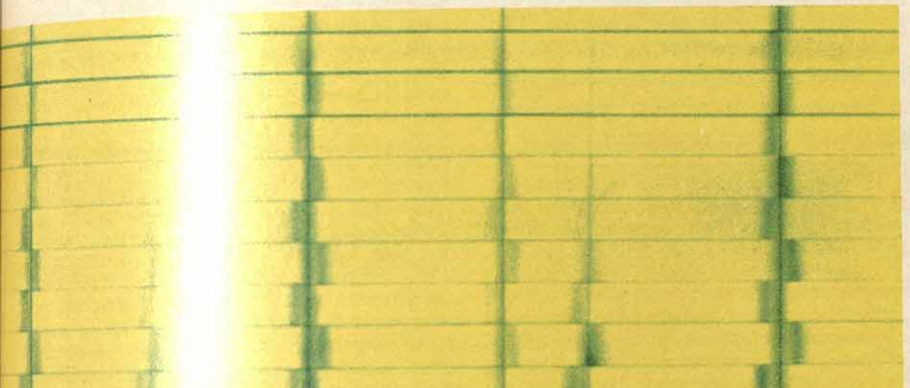


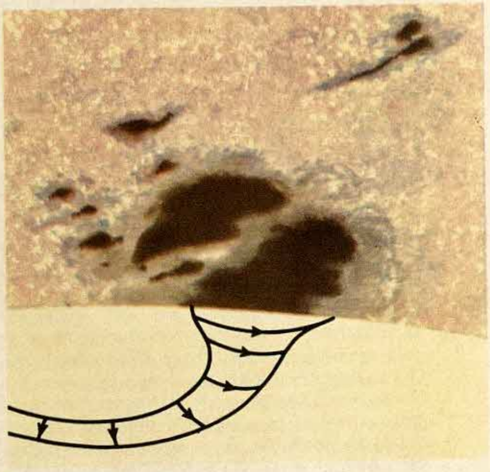
THE SUN'S MAGNETIC FIELDS—Long before it was possible to measure magnetic fields far from the sunspots, photographs like this were taken in hydrogen light with a spectroheliograph. The characteristic flocculation of the hydrogen filaments around the sunspots is similar to the course of the iron filings around the poles of a magnet.

2



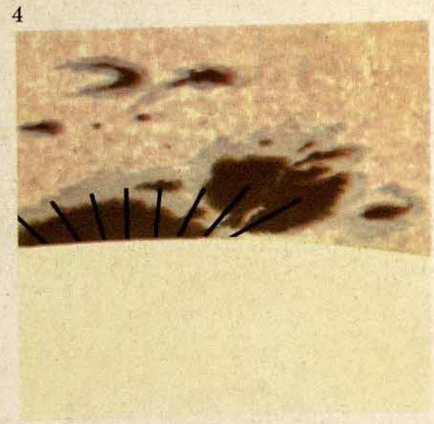
THE LINES SEEN IN HALE'S GRATING—The spectral lines, when enlarged by the magnetic field, appear in this way, as observed in a high-dispersion spectrograph in which the slit is covered by Hale's grating. The lines sensitive to the magnetic field appear strongly serrated.

3



MAGNETOHYDRODYNAMICS AND SUNSPOTS—One hypothesis that could explain various characteristics of sunspots is that the solar material of a sunspot is the site of a vortex. Magnetohydrodynamics, the science dealing with the movement of conductor fluids subject to magnetic fields, would then explain not only the presence of magnetic fields but also the opposite polarity presented by the spots at opposite extremes of a single vortex.

4



MAGNETIC MAP OF A SUNSPOT—The lines of force of a magnetic field on a map are not always perpendicular to the surface of the solar photosphere. They have different inclinations, more vertical at the center and more inclined at the edges. The measurement of this inclination can be obtained by measuring the polarization of the components of the lines subjected to the Zeeman effect.

field of sufficient intensity, these lines split. Where one line was previously observed, the researcher can see two, three, or even more. The distance between the lines depends on the intensity of the magnetic field that produces them.

This phenomenon of spectral lines splitting due to the presence of a magnetic field is known as the Zeeman effect. This effect, named after the Dutch physicist Pieter Zeeman, who discovered and interpreted it, has provided scientists with a basic yardstick for detecting and measuring the magnetic phenomena of the sun.

THE ZEEMAN EFFECT AND THE STUDY OF THE SUNSPOTS

The theory of the Zeeman effect is an important chapter in physics. When a spectral line, suitably selected from the spectrum of an element, is emitted by atoms immersed in a magnetic field it can be observed that, if the magnetic field is pointed toward the observer, the line appears split into two components with opposite circular polarizations. The direction of polarization is inverted if the orientation of the magnetic field is inverted. When the spectrum of a sunspot situated near the center of the solar disk is observed, the splitting of some lines into two components can be detected, indicating that the magnetic field in the center of the spot is directed vertically upward. On the other hand, if the magnetic field is perpendicular to the direction in which it is observed, the spectral line is divided into three components, of which the center component is polarized linearly in a direction parallel to the field, and the two outer components are at a right angle to the central one. When the spectrum of the edges of a sunspot near the center of the solar disk is observed, the lines relating to the Zeeman effect are divided into three components polarized in this way.

THE FIELD OF THE SPOTS

Utilizing the Zeeman theory, the researcher can draw a conclusion about how the lines of magnetic force are distributed in a sunspot close to the center of the solar disk. The lines leave the surface of the sun perpendicularly

from the zone at the center of the spot, while at the edges of the spot they open out fanwise.

A spot that moves by solar rotation to the sun's limb produces another effect. In this case, the researcher can deduce from observation that the center of a spot near the limb of the sun will present lines divided into three components polarized as in the previous case, while the spectrum of the edges of the spot shows lines split into two components and polarized circularly. That is, the spots near the sun's limb behave in a way that is completely opposite to those found at the center of the disk, exactly as expected from the field directions.

The intensity of the magnetic fields of the spots is always quite outstanding—in the range of thousands of gauss (a

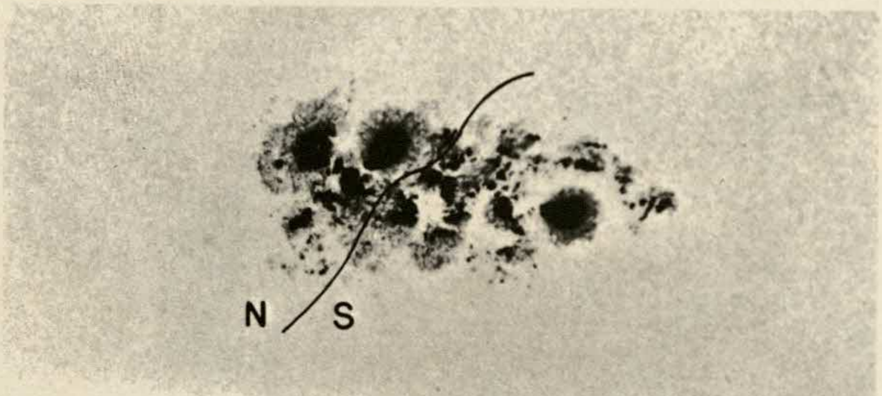
THE POLARITY OF SUNSPOTS—If the direction of the circular polarization of the Zeeman components of a split line is examined, it can be determined whether the spot presents the north or south magnetic pole with respect to an observer on Earth. By means of this system of measurement, it has been discovered that sunspots of both polarities appear on the sun. A systematic study of the polarities of the spots has resulted in a simple classification. All sunspots are the sites of more or less intense magnetic fields. Therefore, different types of sunspots can be distinguished with special instruments.

Unipolar spots (Illustration 5a) appear isolated or in small groups, and all have the same magnetic polarity. Bipolar spots appear as pairs having opposite polarities. In the case of paired sunspots closely surrounded by smaller spots, a line of separation divides those of northern polarity from those of southern polarity. Multipolar spots are groups of large and small sunspots with magnetic fields of different polarities. They could be defined as spots with irregular magnetic fields. Illustration 5b shows a multipolar group of spots in white light, while Illustration 5c shows them in hydrogen light.

MAGNETIC CYCLE OF THE SUNSPOTS—The eleven-year cycle of the number of sunspots doubles if the difference in magnetic polarity is taken into account.

The illustration shows the polarity of the leading spot in a bipolar group. Illustration 6a shows that during a cycle the leading spots in one hemisphere have north polarity, while those in the other hemisphere have south polarity. As the cycle progresses the spots appear, on the average, at lower latitudes. However, the leading spots of the northern hemisphere have a north polarity and those of the southern hemisphere a south polarity (Illustration 6b). At the end of a cycle (Illustration 6c), there are very few spots (at low latitudes) of the old cycle of the polarity that was up to that moment characteristic of that hemisphere, while the spots of the new cycle, which appear at high latitudes, are of reversed polarity. During the next eleven-year cycle (Illustration 6d), the leading spots continue to have prevalently south polarities in the north hemisphere and north polarities in the south. Therefore, the real cycle of the sunspots is 23 years and not 11.5, which would be the length of the cycle if the spots were judged solely on their number.

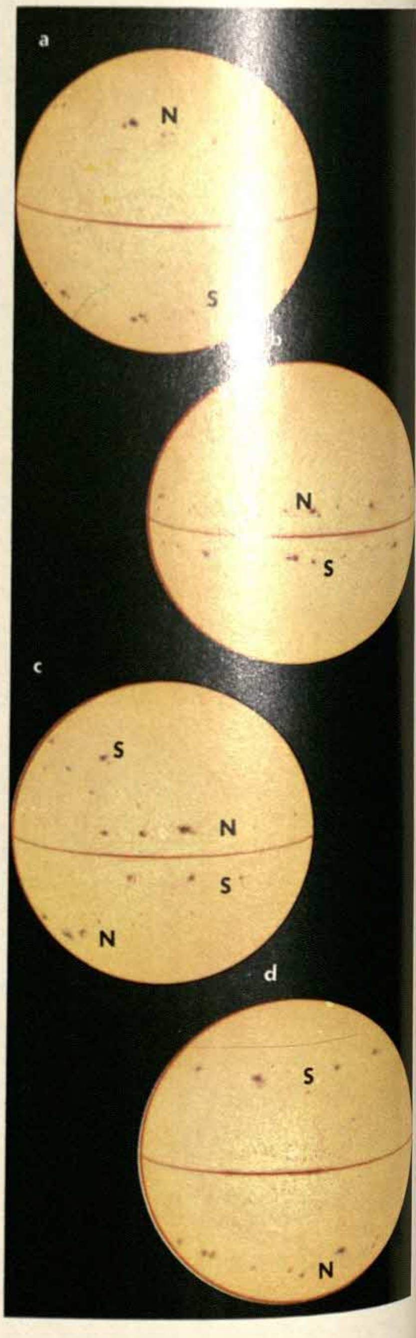
5a



5b

5c

6



measure of magnetic field strength). A value of hundreds of gauss is normal; from 1,000 to 2,000 is quite common. However, astronomers have observed sunspots that have magnetic fields of values up to 5,000 gauss. By comparison, the Earth's magnetic field measures about half a gauss.

THE ELEVEN-YEAR CYCLE AND THE POLARITY OF THE SUNSPOTS

Most sunspots are of the bipolar type, one closely following on the other as the sun rotates. A systematic study, covering many decades, of the polarity of sunspots has established that the bipolar spots have the following characteristics:

1. Sunspots that lead in a given hemisphere always have the same polarity for an entire eleven-year cycle; that is, in all the pairs of spots that appear in a solar hemisphere, the first spot always has the same polarity and the second spot is of the opposite polarity.
2. At the same time, in the pairs appearing in one hemisphere, the first spot has a polarity opposite to a corresponding spot of the other hemisphere.
3. When an eleven-year cycle is ended and a new one begins, the polarity of a sunspot pair is inverted. If, for example, in one cycle in a hemisphere the first spot is south-polarized, it will be north-polarized in the new cycle, and vice versa.
4. At the end of a cycle the last pairs of sunspots to appear are visible near the equator. These pairs obey the rule of the polarity of the cycle.

STUDYING THE SUN WITH THE AID OF THE ZEEMAN EFFECT—The components into which a spectral line emitted in an intense magnetic field are split are quite close to one another. When the field is of about 3,000 gauss, for example, the distance of the components into which a red line splits is about 0.1 Å.

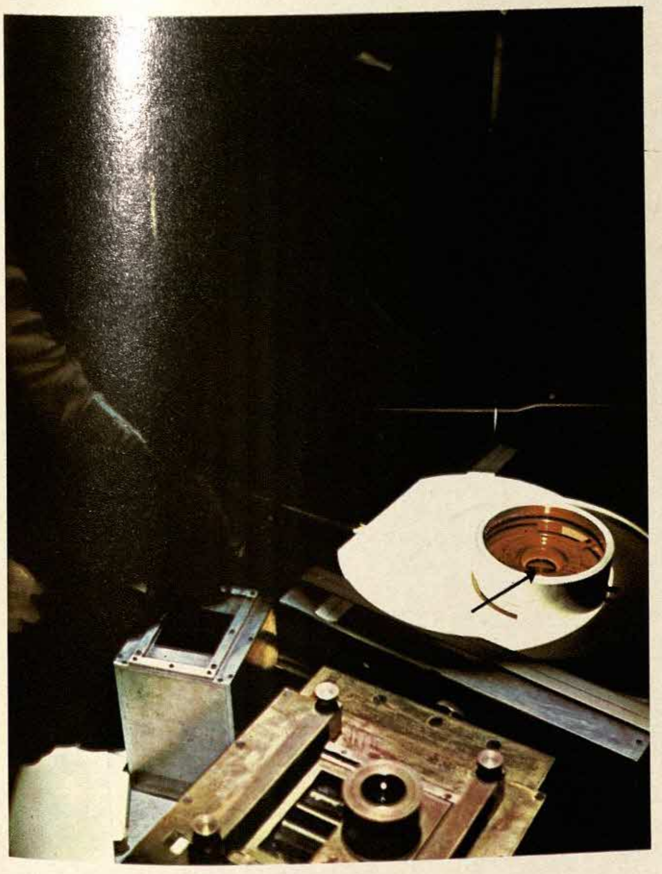
While a large solar spectrograph presents a dispersion of many millimeters per Å, the line may have a width of some tenths of Ångstroms; thus, instead of being seen as doubled or tripled, the line will simply appear to be wider. It will not be possible, however, to know with any certainty the reason for this widening. Consequently, it will not be possible to identify the magnetic field. The situation is made worse when the field is weaker, as it is in the majority of cases. To overcome these difficulties, the instrument shown in Illustration 7a was first developed in 1917 at Mount Wilson Observatory by the American astronomer G. E. Hale. It serves to determine if the wings of a broad line emitted by a spot close to the center of the sun's disk are circularly polarized. The instrument also measures indirectly a solar magnetic field once its presence is revealed. The device consists, as shown in Illustration 7b, of a series of thin plates of mica, each about 1 millimeter wide, which produce a phase delay of one-fourth of a wavelength. These plates **a** and **a′** transform circularly polarized light into linearly polarized light. They are placed in front of the slit of a solar spectrograph, so that the principal sections are perpendicular among themselves and inclined at 45° to the slit. A polarized-light analyzer—a Nicol prism or a birefractive filter **b**—is placed between the plates and the slit.

If a spectral line has been widened by the Zeeman effect, one of its borders will consist of circularly polarized light. All the mica plates in even positions will transform this light into linearly polarized light that passes through the analyzer; the odd plates, meanwhile, block the passage of light through the analyzer. The light from the opposite border is treated analogously but in the opposite way. The borders of a line widened by the Zeeman effect will then appear serrated, and the depth of the serration will be closely related to the intensity of the magnetic field (see Illustration 2).

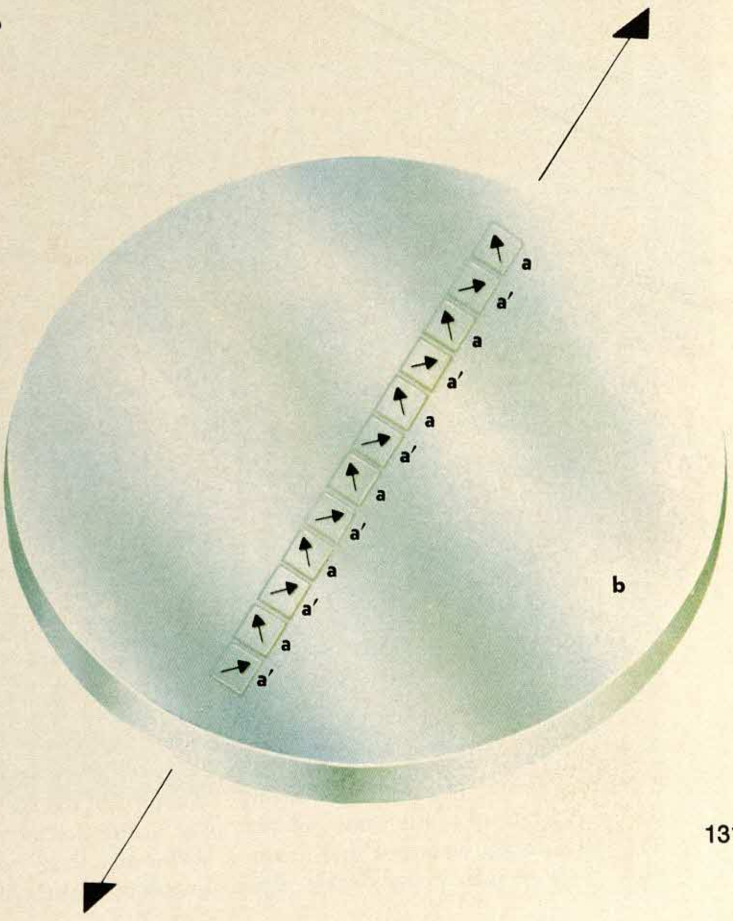
The instrument permits interpretation of many details of the constitution of sunspots. It is possible, for example, to study the magnetic field present in the lower portions of the inverting layer close to the photosphere, evaluating the Zeeman effect in the spectral line of such layers. It is also possible to study the Zeeman widening in a line produced in a higher layer of the photosphere. For example, it has been noticed that above the sunspots the magnetic field rapidly decreases in intensity; in fact, the Zeeman effect cannot be observed in the D line of sodium, produced in a high level of the photosphere; however, the Zeeman effect is rich in lines produced in the lower levels. With these methods it is possible to construct accurate maps of the most intense parts of the solar magnetic field.

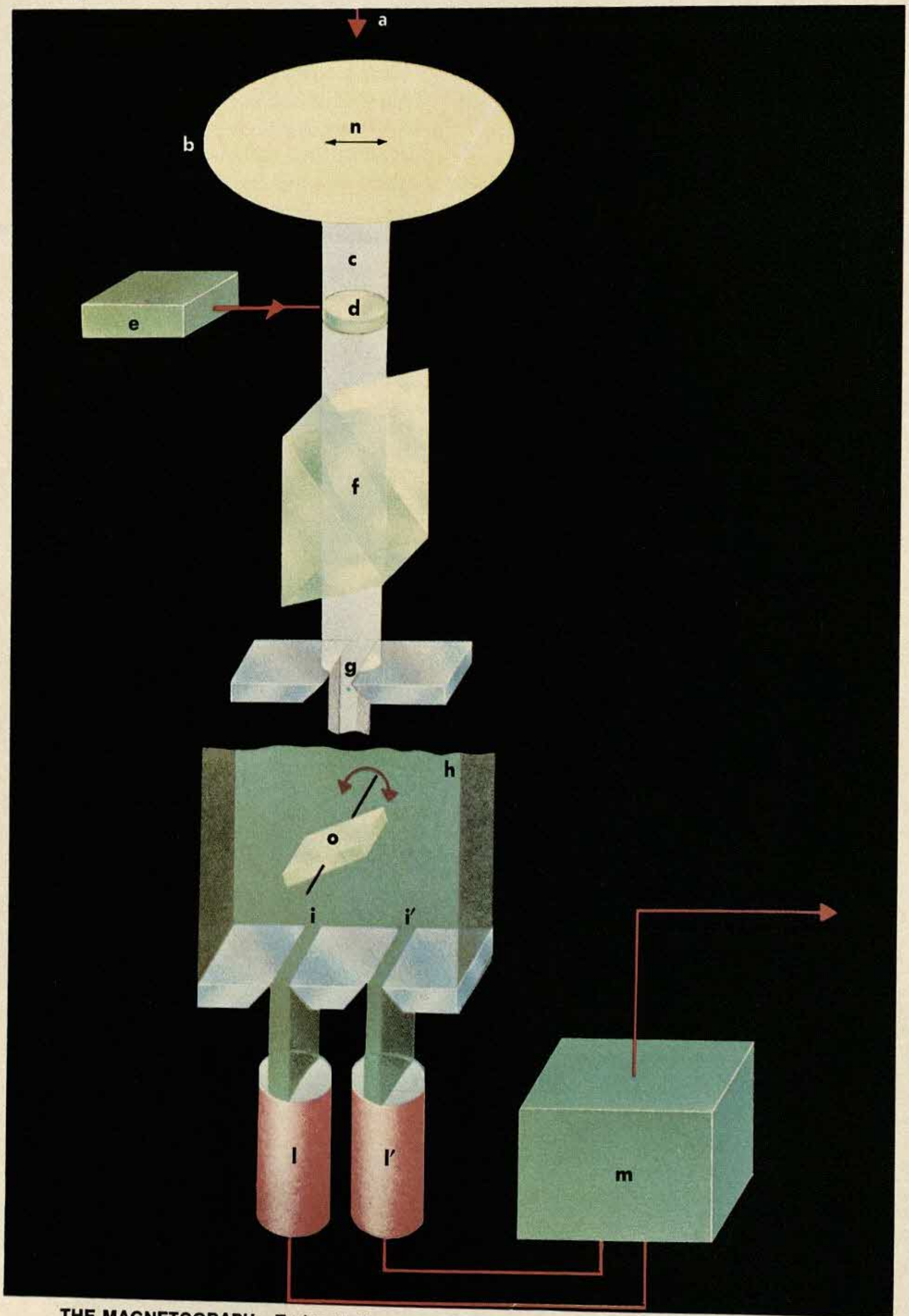
From such studies of the solar magnetic field and of its variation scientists are gaining increasing knowledge of the physical conditions under which solar flares, prominences, and corpuscular emissions generally take place.

7a



7b





THE MAGNETOGRAPH—To locate the general solar magnetic field—and to map the zones in which disturbances in the photosphere give rise to local magnetic fields—special instruments, magnetographs, are used. These instruments measure very weak fields.

It is obvious that measuring the intensity of the magnetic field of a sunspot requires considerable time, because it requires a lengthy photographic exposure of one point of the solar surface. The solar magnetograph, however, explores successively the entire solar surface and detects the widening of the spectral line by means of a system similar to that of the mica grating. This device works with a photometer, which translates the widening of the spectral line into an electric signal. This signal is transmitted to an oscilloscope, which, in turn, indicates the presence of a magnetic field.

By means of the magnetograph it is possible to follow the evolution of the magnetic fields of sunspots over a large region. These fields continue long after the disappearance of the spots with which they are associated. In the same zone other photospheric perturbations are detected and, at a higher level, in the chromosphere and the corona, radio disturbances originate. The connection between all these phenomena is one of the major fields of study in solar physics.

The illustration shows a magnetograph similar to the one built by the American astronomer Horace W. Babcock. The image of the sun **b** arrives from a solar tower a. A small part of this image **c** is passed through a crystalline plate **d**, which, excited by rapidly changing alternating current produced by the generator **e**, functions alternately as a mica plate of the **a** type and as one of the a′ type as in Illustration 7. This plate is followed by a prism that analyzes polarized light f, after which the light is introduced into the slit **g** of a large solar-tower spectrograph. Imagine at this point that, at the exit of this spectrograph (which has not been represented for the sake of simplicity), a spectral line is seen falling, for example, on the green. As a result of the great dispersion of the spectrograph, the shadowy lateral parts of this line, polarized by the solar magnetic fields, fall on the slits, **i** and **i′**, which precede two photometers **l** and **l′**. With the alternating of the optical orientation of the plate **d,** the peripheral parts of a spectral line emitted by a solar region subjected to a magnetic field, which fall on the slits **i** and **i′**, change alternatively in intensity. This change is detected by the differential amplifier **m,** from which the researcher can read directly the intensity of the sun's magnetic field. To develop the complete magnetogram of the solar surface, it is necessary, by means of the mirrors of an instrument known as a coelostat, to move the solar image in the direction of the arrow **n** in order to explore the entire disk and repeat the operation on many equidistant parallel lines. When the magnetograph explores the limbs far from the sun's axis of rotation, the spectral line is displaced by the Doppler effect; therefore, the spectral line no longer falls in the center of slots **i** and **i′**. Consequently, a glass plate **c** is placed in front of the slots. The plate, operated by the same device used to carry out the survey of the sun, rotates so as to bring the axis of the spectral line back into the correct position.

It can happen that at the end of a cycle some pairs will appear at a high latitude, but these already belong to the new cycle and respect its rule; therefore, they have polarities that are reversed with respect to the pairs at low latitudes.

It is clear, from this rule, that two entire eleven-year cycles must pass before the spots again have the same polarity. Therefore, it can be stated that a complete cycle of solar activity takes place not over eleven and a half years but over twenty-three years.

THE SUN'S GENERAL MAGNETIC FIELD

It is not easy to measure solar magnetic fields of hundreds of gauss. These fields, observed in the spots from time to time, last a little longer than the spots themselves and then vanish. This raises the question: does the sun have a permanent general magnetic field?

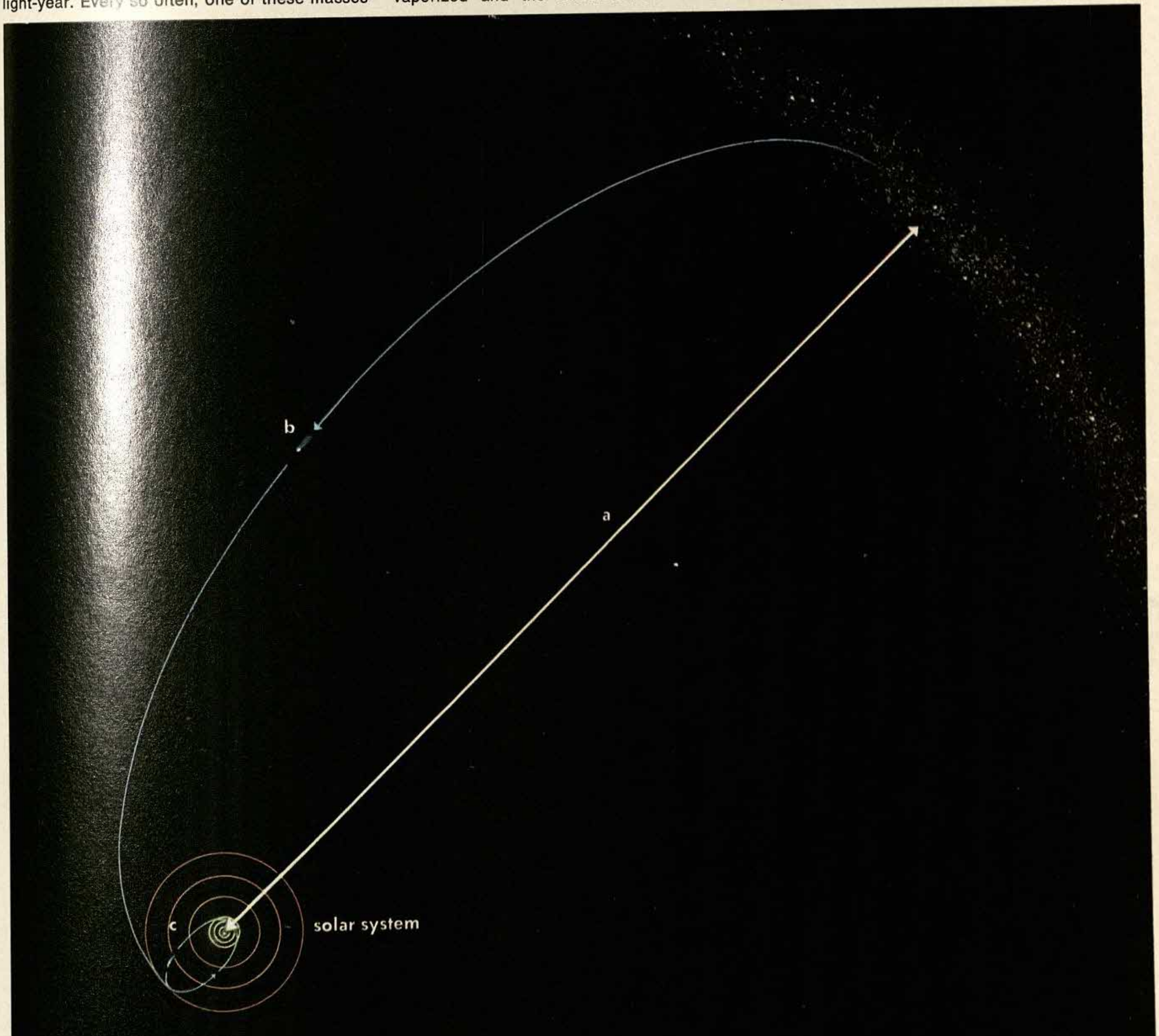
If a permanent magnetic field were present, it would be manifested as a widening of the spectral lines from any point on the photosphere and not just from the sunspots. Because the spectrum of the photosphere is often observed with extremely sensitive instruments, it can be stated with certainty that if such a general field exists it must be extremely weak. Its intensity cannot be greater than some tens of gauss.

COMETS—I | 100 billion objects at the edge of the solar system

In 1577 Tycho Brahe, a brilliant Danish astronomer, demonstrated, by comparison of observations made at two widely separated observatories, that comets are more remote than the moon and, therefore, must be considered celestial objects. Until that time two schools of thought existed concerning the nature of comets: one regarded them as true celestial objects, the other as vaporous exhalations within the Earth's atmosphere.

The confusion over the nature of comets is understandable, considering their irregular appearance and their rapid and often unpredicted movements, combined with the exotic appearance of their tails. In ancient times, men believed that the movement of celestial bodies

CAPTURING A COMET—Hundreds of millions of comets circulate around the sun at a distance **a** far greater than the distances of planetary orbits from the sun—about one light-year. Every so often, one of these masses falls toward the sun **b.** Having entered the solar system **c,** the comet's trajectory can be transformed into an ellipse that makes it pass close to the sun. Then some of its mass is vaporized and the characteristic comet tail develops. In its journey away from the sun, the comet gradually loses speed and finally disappears. The final orbit of the comet depends on its gravitational interaction with the larger planets.



influenced earthly affairs, and comets were regarded with both trepidation and fascination. Later, comets were associated with plagues, famines, and wars. These ideas had the useful scientific result of causing the movements of comets to be noted with great care. The Chinese, in particular, carefully chronicled their movements, and long before Brahe's observations, they recognized that comets were celestial objects.

A comet may be defined as a celestial object revolving around the sun. Its name comes from the Greek word for "hair," suggesting a resemblance between the tail of a comet and long hair streaming in the wind. The term used in China and Japan, translated "besom (broom) star," suggests either a comparison between a comet's tail and the bundle of twigs in a primitive broom, or the sweeping motion of a broom over a floor and the motion of a comet's tail across the sky.

Most comets consist of three parts: a nucleus, a diffuse envelope or coma and, when the comet is close to the sun, a tail. The bright central nucleus may be nearly as large as the Earth; the head, or coma surrounding the nucleus, may be from 48,000 to 160,000 km (about 30,000 to 100,000 mi) in diameter. The tail, which looks like a bright streak behind the comet, may be 160,000,000 km (about 100,000,000 mi) long—longer than the distance between the Earth and the sun. Some comets do not have tails, and appear as hazy, round spots of light.

DISCOVERY OF COMETS

Before the age of photography, comets could only be identified by simple visual observation. This limitation precluded the discovery of comets far distant from the sun. Another problem in identifying comets was (and is) their resemblance to other celestial objects, particularly nebulas. In the last few decades most new comets have been discovered as by-products of other astronomical research on photographs taken with wide-field telescopes.

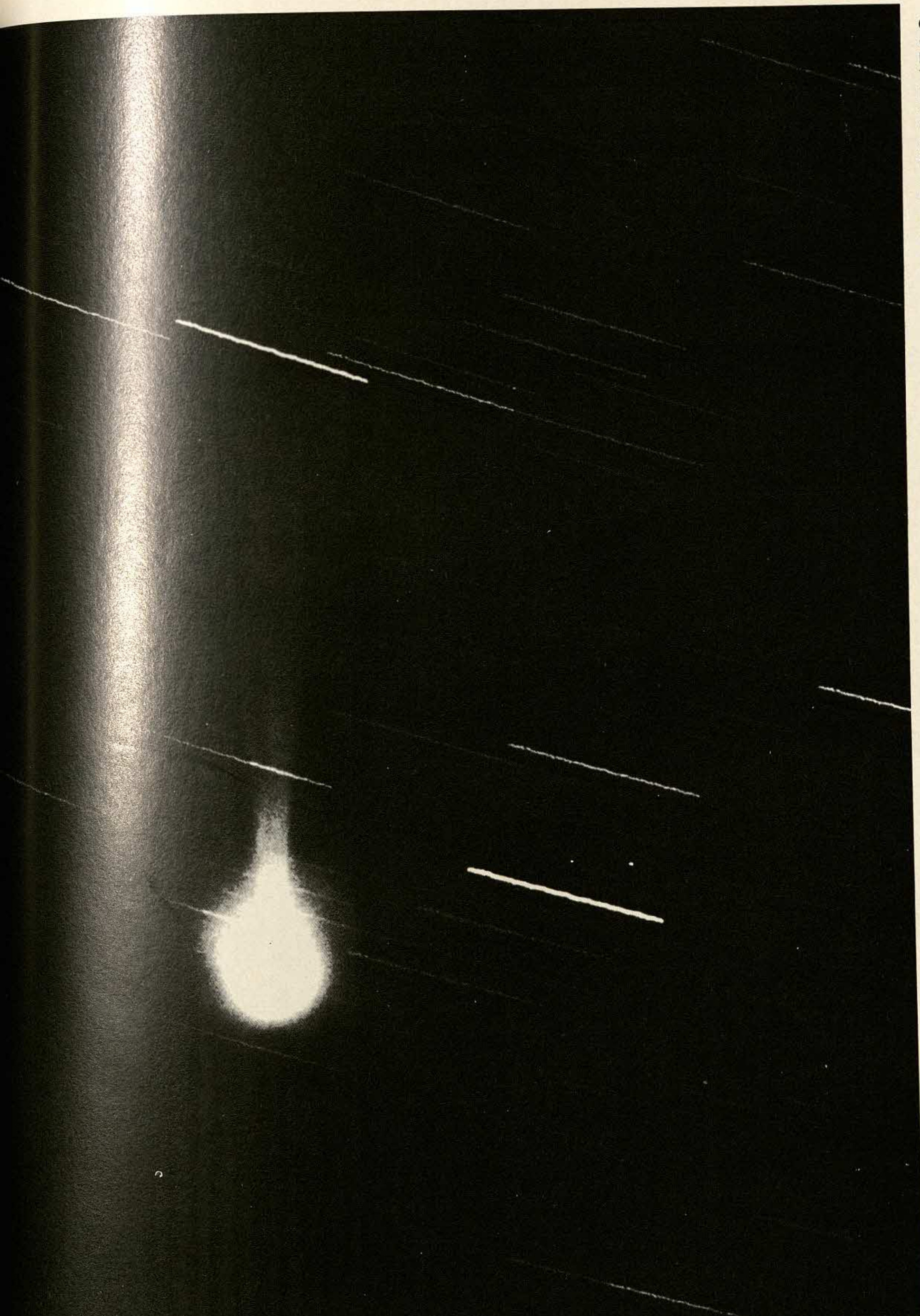
Some comets are discovered as the result of systematic searches by amateur and professional astronomers, but many hours of searching are required for one comet discovery. Through visual observations with powerful binoculars, Czechoslovakian observers recently discovered 17 comets. An average of 206 observation hours was required for the discovery of each comet.

Returns of periodic comets can be predicted, however, and generally only a very limited area in the sky need be examined to ensure re-identification of the comet when it becomes sufficiently bright. Such comets are normally recovered when they are still very faint and at long distances from the sun. The brightest of new comets frequently are seen first close to the sun by casual observers of a sunrise or sunset. Astronomers often neglect that part of the sky. Suspected discovery of a comet should be reported promptly to the nearest observatory for confirmation and in order to communicate details to other astronomers.

ORBITS OF COMETS

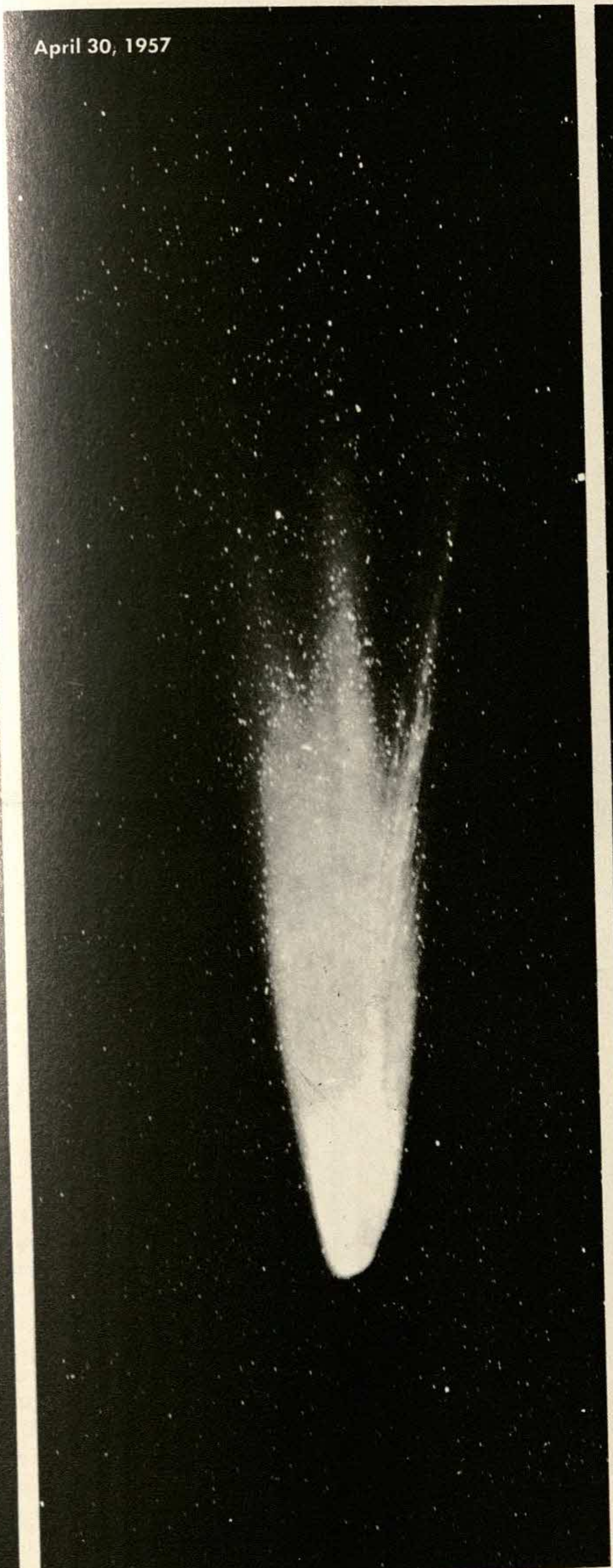
The seventeenth-century German astronomer Johannes Helvelius was the first to suggest that comets move in parabolic paths around the sun. This theory was confirmed a few years later when Isaac Newton formulated the mathematical laws of universal gravitation. Newton proved that under a force that varied in proportion to the inverse square of the distance, a body would move in one of the family of curves known as conic sections: the circle, ellipse, parabola, or hyperbola. The observed movements of comets were explained by the theory that they were traveling around the sun in elongated ellipses or parabolas and were visible only when they described the small portion of their orbits in the neighborhood of the sun.

Newton and Edmund Halley, an English astronomer, collected observational data on comets, beginning with the comet of the year 1337, and calculated their orbits. Halley noticed that the orbits of three of the comets—those of 1531, 1607, and 1682—were nearly identical. The interval between appearances of the comets was not the same—the first being longer by 15 months—but Halley explained this difference as a result of the disturbing action of Jupiter and Saturn. Examination of records revealed that another comet with a similar orbit had appeared in 1456. Halley deduced that all four appearances belonged to a single object whose return could be expected about 1758. The comet did in fact return in



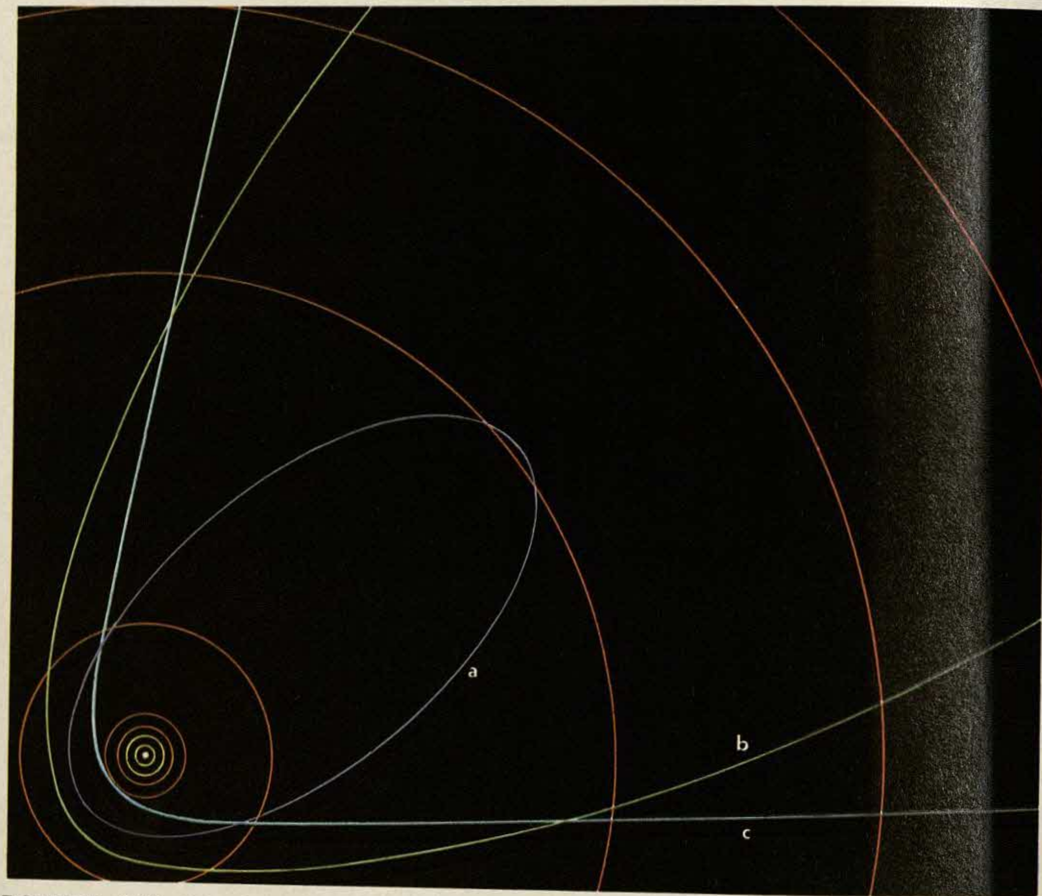
CUNNINGHAM'S COMET, DECEMBER 21, 1940— This small comet has an undeveloped tail and an almost spherical body. The lines in the background are stars, which appear as streaks because the camera followed the movement of the comet.

THE AREND-ROLAND COMET—On April 26, 27, 29, 30 and May 1, 1957, this comet had two tails pointing in opposite directions. The second, very small tail branches off from the nucleus of the comet.



April 30, 1957

May 1, 1957



ORBITS OF THE COMETS—Orbits of the short period comets are flattened ellipses **a**; other comets travel on parabolic **b** or hyperbolic **c** orbits. These orbits are followed by comets that enter the planetary system for the first time. The gravitational attraction of large planets can change the open form (parabolic or hyperbolic) into a closed form (elliptical). This orbital transformation gives the comet a more stable presence at the time it describes the small portion of its orbit in the neighborhood of the sun.

1759, and again in 1835 and 1910, establishing for the first time the fact of a comet's return. This comet is now known as Halley's comet; its next appearance is expected in 1986.

By 1960 the orbits of 829 comets had been catalogued. Some comets make regular visits to the solar system, appearing every 50 years or less, and are called short-period comets; others take more than 50 years to reappear and they are known as long-period comets.

The short-period comets form a very homogeneous group, all revolving around the sun in the same direction as the major planets, in orbits of low inclination to the plane of the Earth's orbit. The aphelia (outermost points) of their orbits all lie close to the orbit of Jupiter. All evidence indicates that these comets were captured by Jupiter from more elongated orbits, and they are considered to be part of "Jupiter's family" of comets.

The total number of comets is estimated to be about 100 billion. Moving at distances two hundred thousand times greater than the distance between the sun and the Earth, these comets are truly in interstellar space; the only strong attraction they experience is that of the sun. At this distance their period of revolution is millions of years. The attraction of a star occasionally changes the force of a comet's orbit, causing it to approach the sun. As the comet nears the sun, it develops a brilliant tail. Gaining in speed, the comet moves toward the sun head-first. Then, as the comet moves away from the sun, it moves tail-first, with the head following; this occurs because the pressure of light and particles from the sun drives off the very small particles from the comet's head to form its tail, always in a direction away from the sun. During its journey away from the sun, the comet gradually loses speed and then disappears from sight.

BIELA'S COMET

Some comets appear periodically and then disappear, apparently forever. One of these rare lost comets was identified in 1826 by the German astronomer Wilhelm von Biela. The comet returned on several occasions, and was observed each time by a number of astronomers. In 1846 it split in two, producing a pair of comets. Eventually both parts of Biela's comet broke into bits too small to be seen. These pieces are thought to form the shower of meteors that appears in the sky in late November.

COMETS—II | the role of solar "wind" in the formation of the tail

Comets, considered by ancient peoples as omens of disaster, are among the most spectacular astronomical phenomena. Usually classified with other natural minor bodies of the solar system (natural satellites, asteroids, and meteors), comets make up in number for their lack of mass. They are fascinating not only from the standpoint of their motion and number but also because of their unusual chemical composition and other special characteristics.

THE APPEARANCE OF COMETS

Generally, a comet is made up of three parts; a nucleus, which is the bright, central part; the coma (which in Latin means "tresses"), a hazy, luminous cloud surrounding the nucleus; and the tail, a long trail of extremely diffused matter. This appearance is assumed for a short period, as a comet passes near the sun. The influence of the sun on the formation of the tail is clearly visible: the closer the comet approaches the sun, the more its tail grows, always in a direction away from the sun.

During past centuries, this characteristic of cometary tails perplexed astronomers, who could not explain how the sun could emit anything capable of pushing away the matter of which a cometary tail appears to be composed. Today, however, astronomers know that the sun's normal radiation—sometimes called the solar "wind"—is powerful enough to repel the extremely diffused matter of a comet's tail. Studies of the sun have shown that the pressure of solar radiation is intense enough to propel into space the matter that makes up certain of the sun's prominences. Inside the sun, moreover, the radiation is so intense that its pressure can support a considerable portion of the weight of the layers of gas that surround the sun's nucleus. The pressure of solar radiation on nearby planets is almost negligible. However, the density of cometary matter is so low that it is pushed away from the comet's nucleus by solar radiation, thus forming the tail of the comet. This matter is lost to the

THE NUCLEUS OF HALLEY'S COMET—This photograph clearly shows matter being pushed away from the nucleus by solar radiation. This matter forms the comet's tail.

comet for good. After several passages near the sun, the comet is completely dispersed.

When comets are far from the sun, they appear as luminous disks with shadowy outlines and no visible tails. At such times, only the head (the coma and nucleus), in which all the comet's matter is concentrated, is visible.

Compared with its colossal size, the comet's mass is so slight that it has never been measured. The most that can be done is to determine the upper limit of the mass.

When a comet passes close to the Earth or any other planet, the attraction of the planet modifies the comet's orbit. If the comet had an appreciable mass, it would provoke perturbations that would modify the orbit of whatever celestial body it approached closely. Observational analysis of the comets that have passed close to the Earth indicates that, in general, their mass is far inferior to the Earth's. Despite their great sizes, their masses are generally equal to those of the smaller asteroids. A mass a million times smaller than that of a small asteroid would amount to something like six billion tons.

CHEMICAL COMPOSITION OF COMETS

Spectroscopic analysis of comets is difficult because of their vast dimensions and the faint light they emit. Despite this, important data have been obtained on their chemical composition.

The nucleus of a comet shows essentially a reflected solar spectrum. The coma and tail show emission spectra, as the gas of which they are composed is excited by solar radiation. In these spectra appear lines and bands of molecules and radicals (characteristic of the lighter elements), as well as of ionized molecules and isolated atoms. These molecules include $(CN)_2$, C_2, C_3, NH, HN_2, CH, and Na. Among the isolated atoms are Na, O (ionized), Fe, and N.

The composition of the nucleus differs from that of the tail. However, the important point is that the most plentiful substances (those most frequently observed spectroscopically) are cyanogen (CN), diatomic carbon (C_2), and carbon monoxide (CO^+). The discovery during the nineteenth century of the presence of cyanogen in comets gave rise to fears that a comet passing near the Earth might poison the atmosphere. However, the amount of cyanogen in a comet would not be enough to poison the entire mass of the Earth's atmosphere. In addition, the cyanogen molecules would be destroyed on contact with the air.

The nucleus of a comet can be pictured as a mass of meteoric material and frozen gases that evaporate under the sun's heat, giving birth to particles that become volatile. These particles, pouring out into space, are the origin of the coma and the tail.

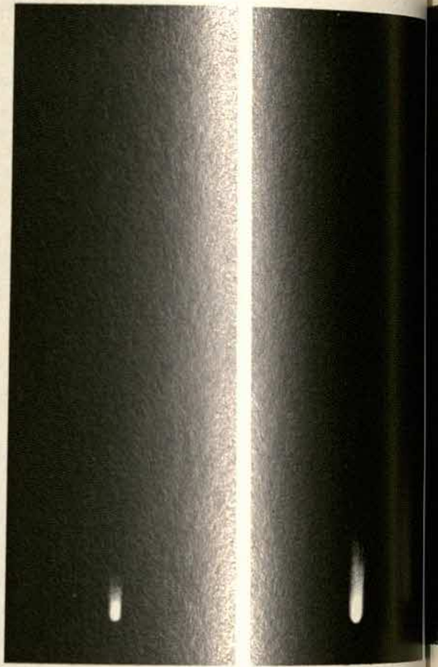
THE FALL OF A COMET

On June 30, 1908, an object fell along the course of the Stony Tunguska River in central Siberia. This object at first was believed to be a gigantic meteorite or an asteroid. The fall was accompanied by dramatic visual and acoustical phenomena, which were perceived up to 1,500 km (about 900 mi) away and were registered on instruments all over the world.

The few spectators in this remote, sparsely settled region saw a shining ball of fire flash across the sky from southeast to northeast, leaving behind a trail of smoke. Flames and smoke reaching a height of about 20 km (about 12 mi) were seen to rise from the point where the object fell. The light of the fireball was seen up to 600 km (about 373 mi) away. When the phenomena were no longer visible, loud explosions were registered as far away as 1,000 km (about 620 mi). On a farm near Vanavara, 60 km (about 37 mi) from the point of the fall, a man was thrown to the ground and lost consciousness.

After the sound wave had become too faint to be heard, it was picked up by the microbarograph stations surrounding

2a



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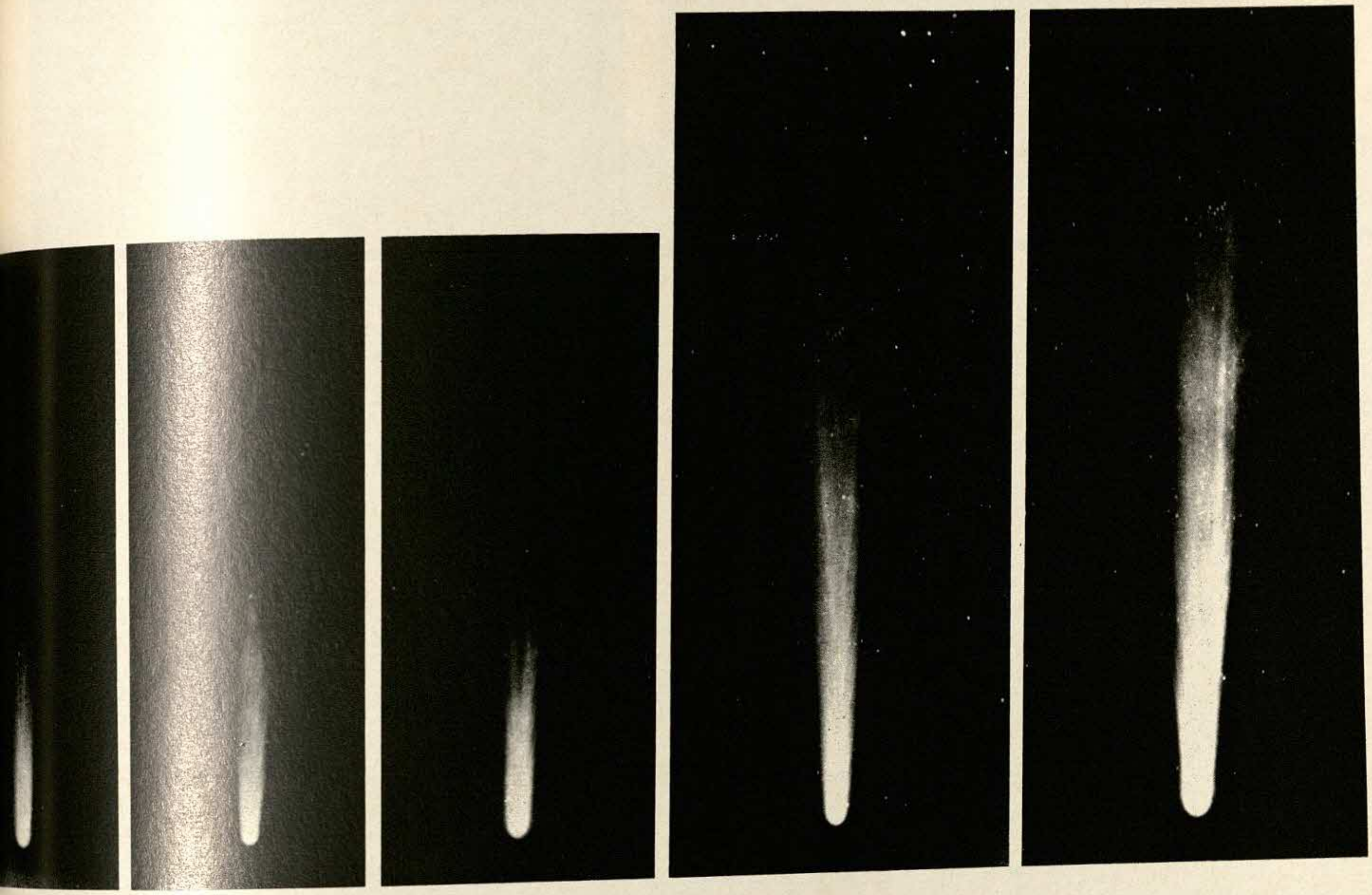
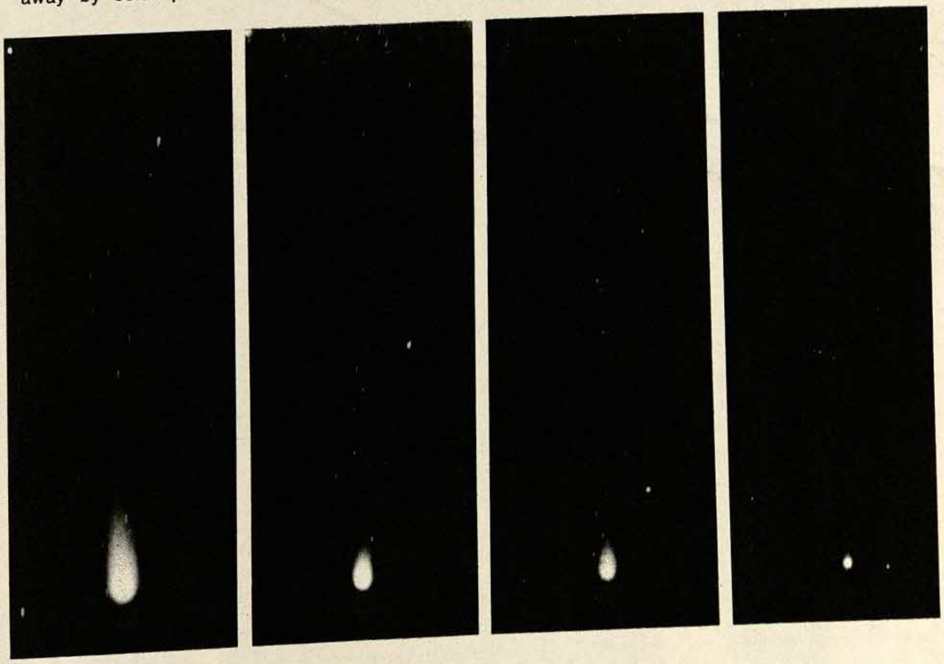


ORIGIN AND DEATH OF COMETARY TAILS— The pressure of solar radiation is strong enough to push away from a comet's nucleus the matter forming the tail. When the comet is near the sun, therefore, the tail is long; when the comet is far away from the sun, the tail is short. Once the matter is torn from the comet's nucleus, it is pushed ever farther away by solar pressure and becomes ever more rarefied until it is dispersed in space. For this reason, it is not possible to detect the exact end of a comet's tail as it fades away into nothingness.

Illustration 2a shows the gradual lengthening of the tail of Halley's comet as it reaches its closest point to the sun, and then the tail's disappearance as it gradually moves away from the sun (Illustration 2b).



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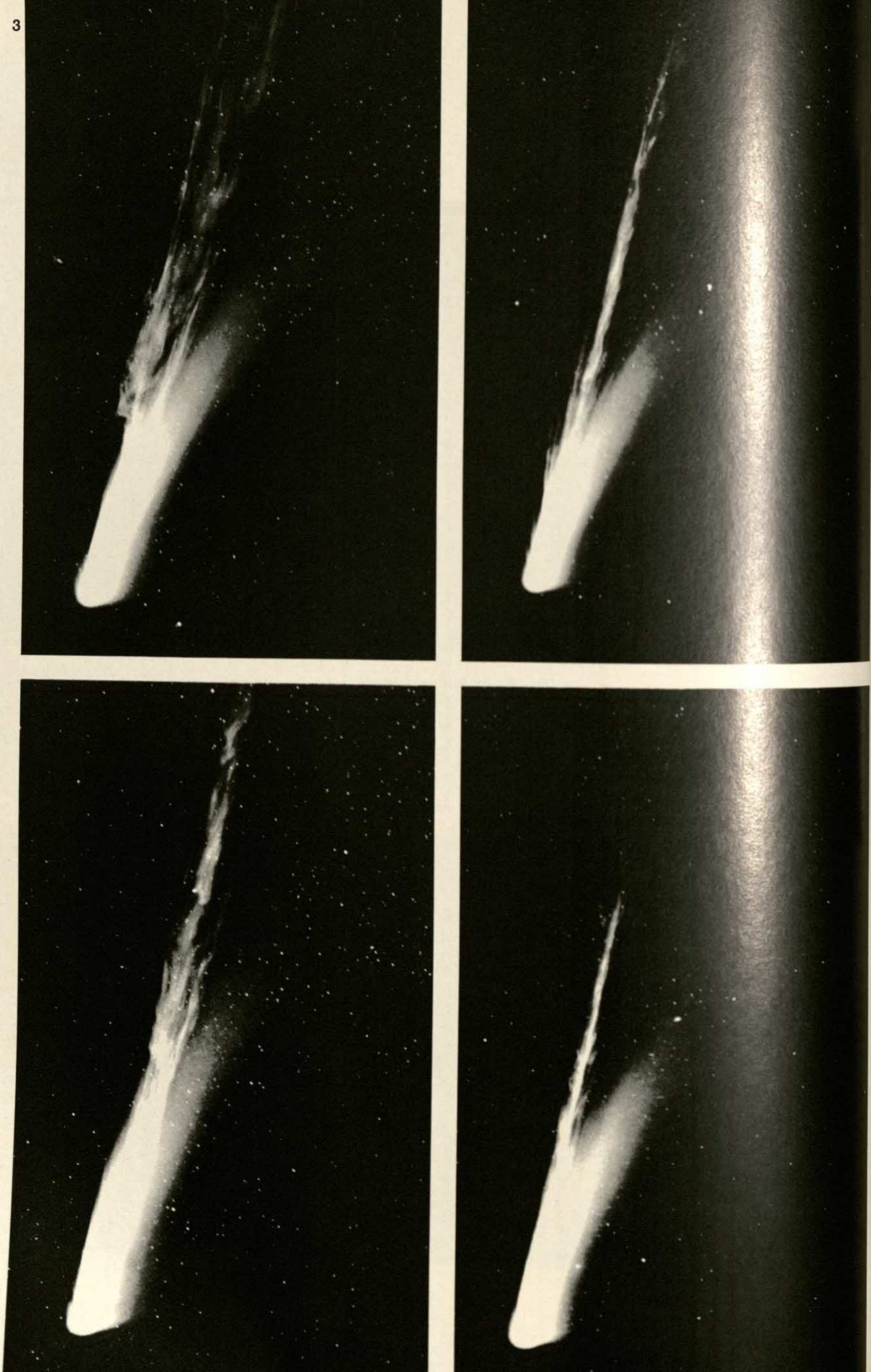


A BEAUTIFUL DOUBLE TAIL—A comet may develop a double tail. Shown in Illustration 3 is the double tail of the comet Mikos as it nears the sun.

4

THE RAPID MOTION OF COMETS—When a comet is close to the sun, it is also relatively close to the Earth. As a result, its position in the sky changes very rapidly.

In photographing a comet, an exposure of a few hours may be necessary to bring out the finer details of the tail. Because the camera follows the motion of the comet, the stars appear as streaks. The colors in this photograph are not real but are due to the fact that, in zones having different luminosity, true colors cannot be correctly reproduced when the exposure time is too long or too short.

Siberia. Some of the stations received both the direct wave and that which had gone around the Earth. Siberian seismographic stations recorded a considerable earth tremor.

The night after the fall of the strange object from space, the sky appeared exceptionally luminous. The light was bright enough to read by. During the following nights the luminosity gradually faded until it disappeared at the end of August.

When the first scientific expeditions reached the spot nineteen years later, it was discovered that the force of the explosion had uprooted the trees over a radius of 30 to 40 km (about 18 to 25 mi). Many trees still lay in positions indicating the center of the phenomenon. Neither a crater nor positively identified meteorite fragments were found near the center. A large part of the forest was burned, indicating that the phenomenon was accompanied by an intense emission of heat.

The lack of a meteor crater of a size proportional to the extent of the phenomenon, the lack of meteorite fragments, the optical phenomena following the fall and the enormous energy given off led researchers to declare that the fiery object might have been a comet. The mass of a cometary nucleus in collision with the Earth would have caused the optical and acoustical phenomena, as well as the impact that caused the earth tremor and the pressure waves. The comet's tail, on the other hand, would have produced the unusual luminescence and the temporary turbidity of the Earth's atmosphere in the ensuing months.

METEORS | fragments of celestial bodies

"Shooting stars" and "falling stars" fascinated man for many centuries before he concluded that they were not stars at all, but objects from outer space that seemed to perish in the alien atmosphere of Earth. Without warning, a luminous streak—sometimes white, sometimes colored—would appear momentarily in the sky. This streak—the trail of a meteor—is a fragment of a celestial body. Most meteors produce faint trails in the sky; a few leave trails whose light is brighter than that of the full moon. Most meteors are destroyed in the atmosphere. The few that reach the surface of the Earth as solid bodies are properly known as meteorites.

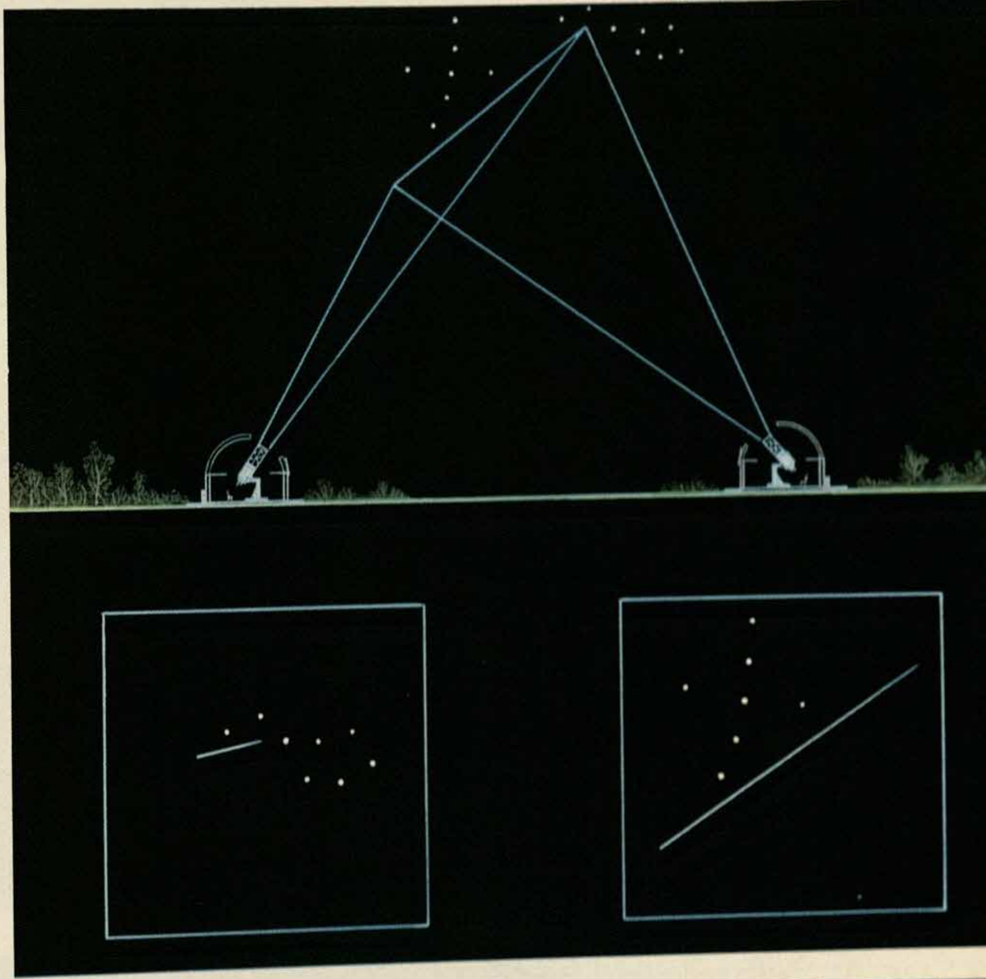
WHAT ARE METEORS?

Meteors are fragments of stone or iron (or some combination of the two) that become visible after entering the Earth's atmosphere. Most meteors are very small, with masses of a few milligrams or grams. They move in space at speeds ranging from a few kilometers to more than 100 km (more than 60 mi) per second. When these fast-moving bodies enter the atmosphere, they are heated to incandescence by friction against the gas molecules that make up the Earth's atmosphere. A meteor moving at a speed of only 10 km (about 6.2 mi) a second has enough energy to vaporize completely on contact with the atmosphere. The velocity of a meteor does not decrease appreciably as it passes through the upper atmosphere. The energy of the meteor is dissipated mainly in the process of melting and vaporization. A meteor rarely becomes heated or vaporized at an altitude of more than 200 km (about 125 mi). Very few meteors have a mass great enough to survive an altitude of less than 100 km (about 62 mi).

SLENDER STREAK—The fall of meteors through the Earth's atmosphere can be studied in four ways: (1) by visual means in which a group of observers watch an area of the sky and, on seeing a meteor, try to determine the beginning and end points of the visible trajectory; (2) by using radar to detect the presence of ionized gas produced by the passage of a meteor; (3) by using cameras that register both the trajectory and velocity of a meteor, and (4) through photographs, made for other observational purposes, that reveal the presence of meteors.

OBSERVATION OF METEOR TRAILS—Two observers several kilometers apart see the same meteor at the same time from different angles and against the background of different constellations. If each observer notes the identity of stars visible near the beginning and end points of the visible trail of the meteor and if the distance between the observers is known, it is possible to re-create the path of the meteor (Illustration 2).

2

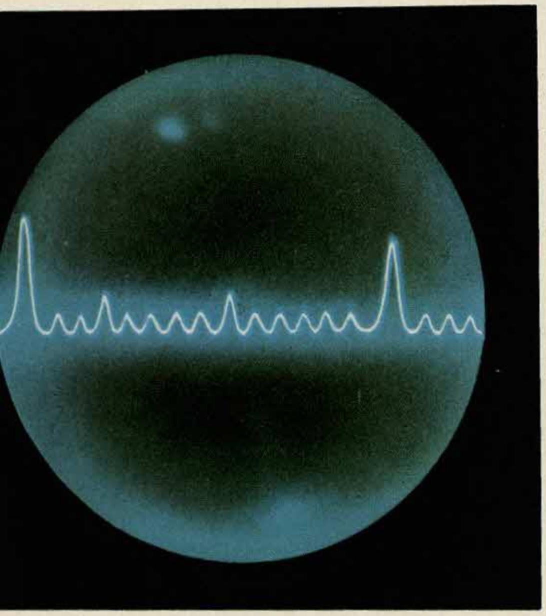


3

PHOTOGRAPHIC OBSERVATION OF METEORS—Two cameras kilometers apart photograph the same area of the sky (Illustration 3). The shutters of these cameras open and close once every 0.01 sec, recording the trail of a meteor as a dotted line. By this means it is possible to measure the velocity of a meteor at various points.

RADAR ECHO OF A METEOR—Radar equipment will detect the passage of a meteor through the atmosphere and, when used with other electronic equipment, produce an echo such as that shown here.

4



TELECOMMUNICATION BY MEANS OF METEORS—Ionized air produced in the upper atmosphere by the passage of a meteor reflects a beam of microwaves back to a distant receiving station on the Earth, thereby temporarily overcoming the limitations of microwaves, which travel in a straight line.

5

OBSERVING METEORS

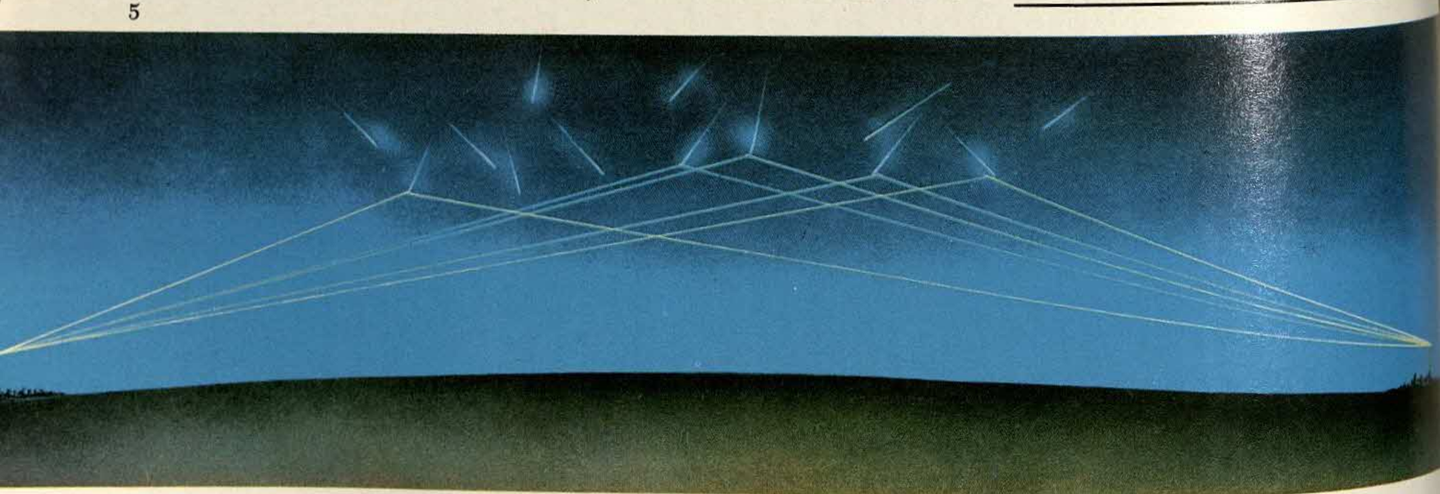
The point at which a meteor becomes visible from the Earth is that point where the meteor begins to heat up in the atmosphere. The point at which the meteor disappears is that point where its destruction by the heat of friction is complete. By reconstructing the exact position of the beginning and end points of the visible path of a meteor, it is possible for two observers at two different locations to establish the trajectory of the meteor and to calculate that area in the solar system from which it came. Calculations are expedited if the stars that appear near the beginning and end of the meteor's visible path can be identified. Pairs of stations have been established for the observation of meteors. The two stations of each pair are 50 to 100 km (about 30 to 60 mi) apart and are equipped with cameras aimed at the same area of the sky. The cameras photograph the same meteor in rapid succession and record on each photograph the moment of exposure, enabling precise location of the beginning and end points of the visible path.

Because of the rotational movement of the Earth, far fewer meteor trails are seen in the period from sunset until midnight than in the hours between midnight and sunrise. In this latter period an observer sees overhead that part of the sky in whose direction the Earth is moving in its orbit around the sun. Meteor sightings are most frequent during this period because, in a sense, the meteors are meeting the Earth head-on. This accounts for what appears to be a daily variation in the number of meteors. An annual variation also exists. In autumn an observer sees overhead that part of the sky in whose direction the entire solar system is moving. Meteors appear most frequently during this season. The daily variation concerns the number of meteors from all sources while the annual variation concerns the number of meteors coming from beyond the solar system.

It is impossible to determine how many meteors strike the Earth each day. A few large meteors, a greater number of small meteors, and an enormous number of microscopic meteors strike the Earth's atmosphere. However, the total mass of meteors that fall daily has been estimated, as shown in the following table:

TOTAL MASS OF METEORS THAT FALL EACH DAY

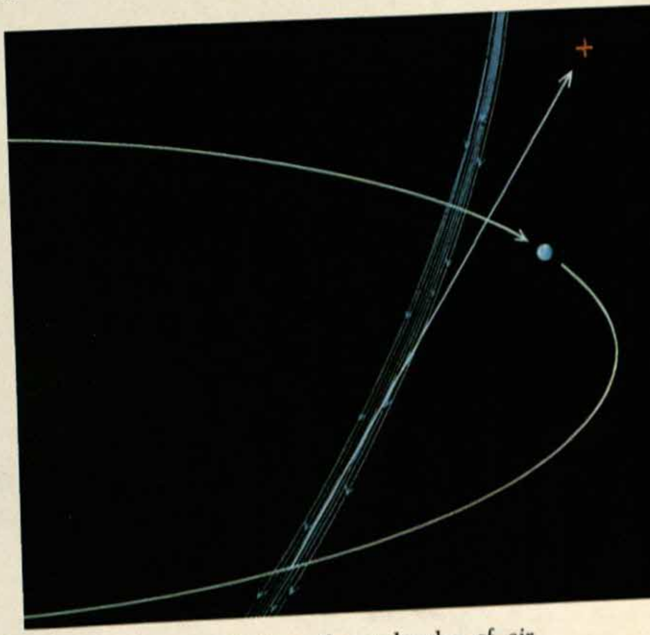
meteors per day	minimum mass (g)	total mass per day (tons)
1.5	10,000	2 t
1,000	100	0.3 t
1,000,000	1	2 t
200,000,000	0.01	6 t
20,000,000,000	0.0001	6 t
>20,000,000,000	<0.0001	1,000 t



6a

THE RADIANT—When meteors travel in parallel paths toward the Earth, they seem to radiate from a point in the sky known as the radiant, indicated by a cross (Illustration 6a). In the inset (lower right), an observer (red point) sees the trails of meteors moving directly toward him or to one side of him. In Illustration 6b, the radiant indicates the tangent to the orbit of the meteor swarm that enters the Earth's atmosphere. If the swarm is dense, the radiant may be fairly obvious; otherwise, it may be reconstructed by observing many successive meteor trails.

6b



Most meteorites have masses of less than 0.0001 g (about 0.000003 oz). They account for almost the entire total mass of meteorites that reach the Earth on one day, about 1,000 tons. As all meteorites show peculiarities not observed in any terrestrial mineral, experts and even laymen usually can identify them easily.

METEOR TRAILS AND THEIR ELECTRICAL CHARACTERISTICS

Trails of the smaller meteors are barely visible to the unaided eye. The light of the trail depends not only on the mass of the meteor but on its velocity, composition, and form. The most frequent meteors, those with a mass of less than 0.0001 g, produce trails whose luminosity is equal to that of a star of the 11th magnitude when the meteors are at an altitude of 200 km (about 125 mi) and observed from directly below. These trails cannot be seen by the unaided eye. Those meteors with a mass of about 0.01 g (about 0.0003 oz) have the brightness of stars of the 5th magnitude; those with a mass of 10 to 100 kg (about 22 to 220 lbs), the brightness of the moon. Extremely large meteors have produced light as bright as that of the sun, illuminating their point of fall as if it were day.

The light of a meteor comes from the incandescent vapor into which it is transformed and from the molecules of air excited by passage of the meteor. In the case of a large meteor, the atmosphere surrounding its trail may remain luminous for hours after the vapor formed by the transformation of its mass has cooled. Passage of the meteor excites the rarefied air, which, after a delay, begins giving off light. The meteor also ionizes the air, striking the molecules and atoms so violently that they lose electrons. Air is normally an insulator, but ionized air becomes a conductor of electricity. Because radio waves are reflected by that part of the atmosphere ionized by a meteor, its trail can be detected by radar. Radar is used to detect the presence of

DEATH IN THE ATMOSPHERE—The atmosphere acts as a shield that protects the surface of the Earth from constant meteorite bombardment. The collision of meteors with atoms of atmospheric gas occurs at a velocity of tens of km per second. At this velocity atoms are torn from the meteor in the form of luminous ionized gas, which causes the characteristic trail seen in the night sky. Destruction of a meteor takes place in an unpredictable manner that depends on its degree of rotation and the number of fragments broken off; thus, the brightness of a meteor path is irregular.

meteors too small to be photographed or seen by the unaided eye, to determine where ionization occurred, and to carry out daylight observations that would be impossible by optical means. Radar enables an observer to take advantage of the fact that ionization of the atmosphere lasts much longer than the luminous trail, which might be visible for only a few seconds or a fraction of a second. Ionization may remain for some minutes.

METEORS PUT TO PRACTICAL USE

Telecommunications engineers have attempted to put ionization of the atmosphere to use in long-distance communications. Normally, communication by microwave between two stations a great distance apart is impossible because a beam of microwaves travels in a straight line and is not reflected appreciably by the atmosphere. Microwaves transmitted from these stations to a point in the sky halfway between them are normally lost in space. However, if a beam intersects a meteor trail, the microwaves are reflected back to Earth and can be picked up by the receiving station. Such transmissions are interrupted when ionization ends, usually after a few minutes, but begin again when another meteor passes. This means of transmission is at times possible but not practical, due to the sporadic and somewhat unpredictable nature of meteors.

METEOR SWARMS

On any clear night many meteors may be seen in different parts of the sky. On some nights a great many meteors may be seen coming from the same direction. It may seem that hundreds, thousands, or tens of thousands of meteors are showering from one point in the sky. In 1833 such a great number of meteors were seen that observers believed the Earth had encountered a meteor swarm moving around the sun. Before that time meteors had been considered an atmospheric phenomenon. From then on, however, it was clear that meteors were an astronomical phenomenon.

The Earth's encounter with meteor swarms gave rise to the term "meteor showers." That point in the sky from which such meteors seem to originate is known as the radiant. The position of the radiant depends on the direction and velocity of the Earth's movement and on the disposition in space of the orbit in which the meteors move. Studies indicated that many meteor swarms follow the orbits of comets and that these meteors could be fragments of the comet, dispersed along its orbit. Many meteors occur in the orbit of a visible comet. Other meteors occur in the orbit of a comet that has been destroyed by the gravitational attraction of a planet. In some cases a particular meteor shower cannot be associated with any comet.

A meteor shower does not occur with the same intensity every year, because the period of revolution of meteors around the sun is not always comparable to the period of revolution of the Earth, and the meteors are not distributed uniformly along their orbits. The following table lists some of the more important meteor showers:

METEOR SHOWERS

name of shower	mean date	velocity, km/sec	comet	no. per hr
Draconid	28 June		Pons Winnecke	50 (1916)
Arietid	6 June	38		60
Perseid	11 August	60	1862 III	50
Giacobinid	9 October	23	Giacobini Zinner	20,000 (1933)
Bielid	14 November	16	Biela 1826	10,000 (1885)
Leonid	16 November	72	1866 I	10,000 (1883)
Geminid	13 December	35		50

METEORITE TYPES | from their origin to their encounter with the Earth

The Earth, in its wide-ranging orbit around the sun, is constantly bombarded with debris from the solar system. Much of this bombardment—the fallout of tiny fragments of celestial dust produced by the disintegration of comets, asteroids, and meteoroids far out in space—goes unnoticed, even though it adds some 2 million tons of matter to the Earth's surface annually. However, other phases of this bombardment—particularly the fiery "death plunge" of meteors into the Earth's atmosphere—are spectacular sights.

A large percentage of meteors are small, ranging in size from a pebble to a boulder. These meteors end their lives in the furnace created by their friction in the Earth's atmosphere. Larger meteors, however, are not completely consumed by vaporization during their earthward flight. The remnants of meteors that partially survive the intense heat of atmospheric friction are called meteorites.

The blazing journey through the atmosphere not only erodes a meteorite but also slows its velocity considerably. After entering the atmosphere at the high velocity of a body traveling freely in space, the meteorite is slowed down to only a few miles per second by the time it reaches the Earth's surface.

A few giant meteorites, weighing thousands of tons, strike the Earth with their velocity little checked. Hitting the Earth's surface at such a high velocity results in a release of kinetic energy sufficient to melt and even volatilize the meteorite; this rapid release of energy causes a violent explosion. Thus, the entry of a giant meteor into the Earth's atmosphere produces turbulent shock waves having destructive effects over a wide range, and the explosive power of its contact with the Earth gouges enormous craters. Fortunately, the collision of giant meteorites with Earth is rare, occurring only about once every 10,000 years.

METEORITE DUST

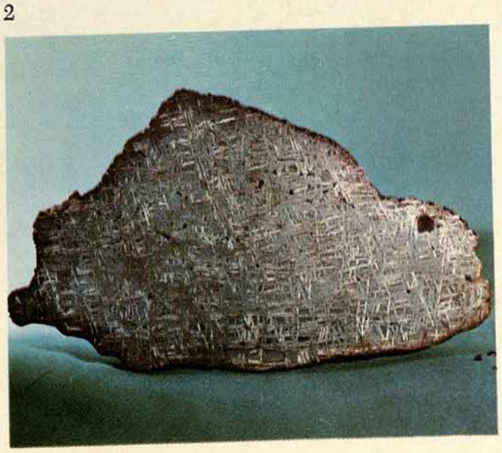
When a meteorite is disintegrated by the heat of atmospheric friction, the gas into which it is vaporized condenses quickly. If the meteorite is composed principally

1

A RECENT ENCOUNTER—On February 12, 1947, a shower of meteorites fell at Sikhote-Alin in eastern Siberia. The meteorite fall produced 106 small craters, the largest of which was 28 m (about 91 ft) in diameter. The impact area is spread across approximately 0.7 km^2 (about 0.27 mi^2). A fragment of one of these meteorites is shown.

THE WIDMANSTÄTTEN PATTERN—The structure of iron meteorites is revealed by etching a polished cross section of the meteorite with dilute acid. The surface of a cut and polished meteorite appears quite uniform. When the surface is treated with dilute acid, the nickel that has formed isolated crystals remains shiny while the iron darkens. The etched outlines of nickel crystals, as shown here, form what is known as the Widmanstätten Pattern.

2

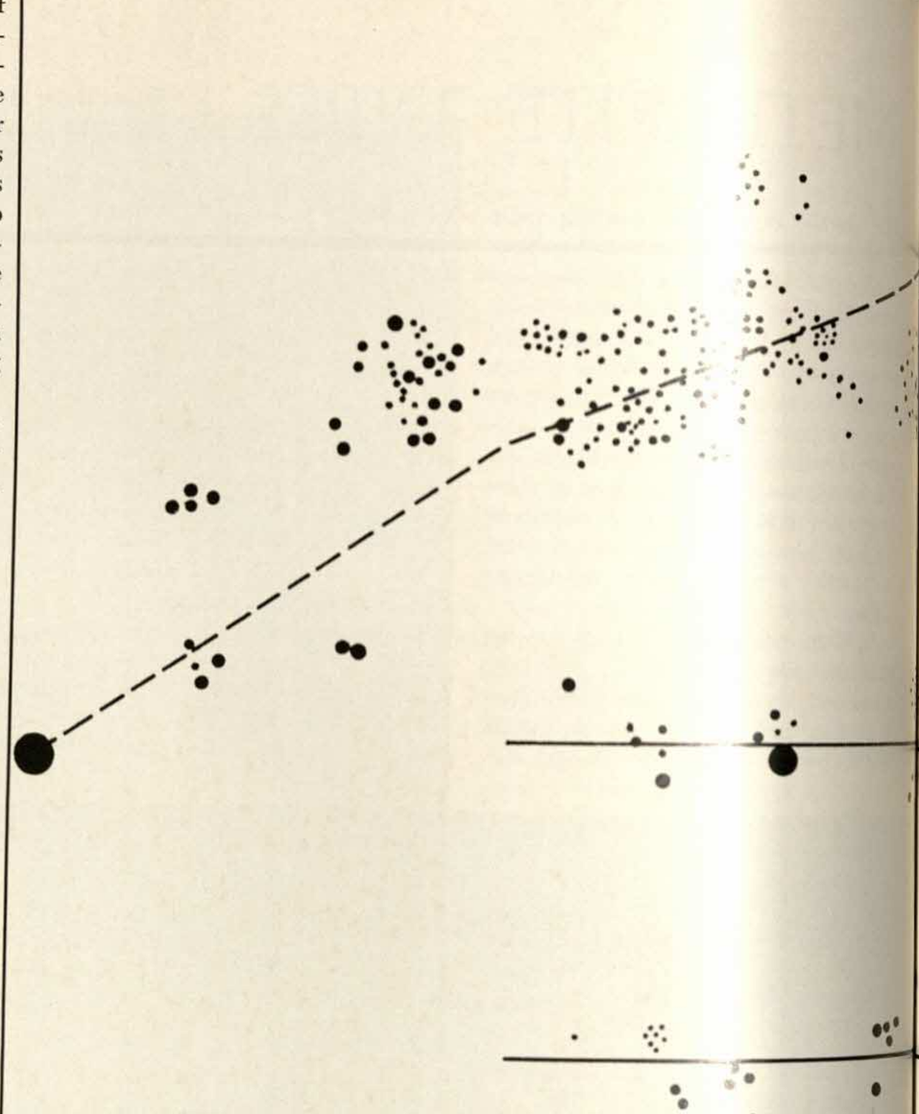


of iron and nickel, the gas condenses into a dust containing minute particles of iron, nickel, and oxides, and these particles fall to the Earth's surface. The velocity of fall depends on the size of the particles and on the density of the air through which they descend. The fall is rapid in the more rarefied upper layers of the atmosphere, and then is slowed to a gradual downward drift by the increasing density of the air. Finally, in the troposphere, currents of rising air frequently cause the particles to rise again for a period of time before finally settling to Earth.

Upon reaching the ground the particles generally are quickly dispersed by the erosive action of water and air. On mountaintops, however, the spring snows are often covered by a light layer of meteor dust almost invisible to the eye. At heights where the density of the air prevents the dust of the plains from rising, a magnetic dust, composed of the condensation of vapors of the same metals that make up meteorites, clearly shows an extraterrestrial origin. Moreover, the same dust, with the same composition and the same appearance, can be gathered in small quantities by powerful magnets at any point on the Earth's surface.

It has been theorized that the ooze of the ocean depths, which is located too far from coastal regions to be alluvial river deposits, may have been formed in part by the disintegration and sedimentation of this extraterrestrial dust. In recent years, various oceanographic expeditions have sought to prove this theory by collecting and analyzing samples of deep ocean ooze in a search for meteorite traces. To date, however, no conclusive evidence has been collected.

4



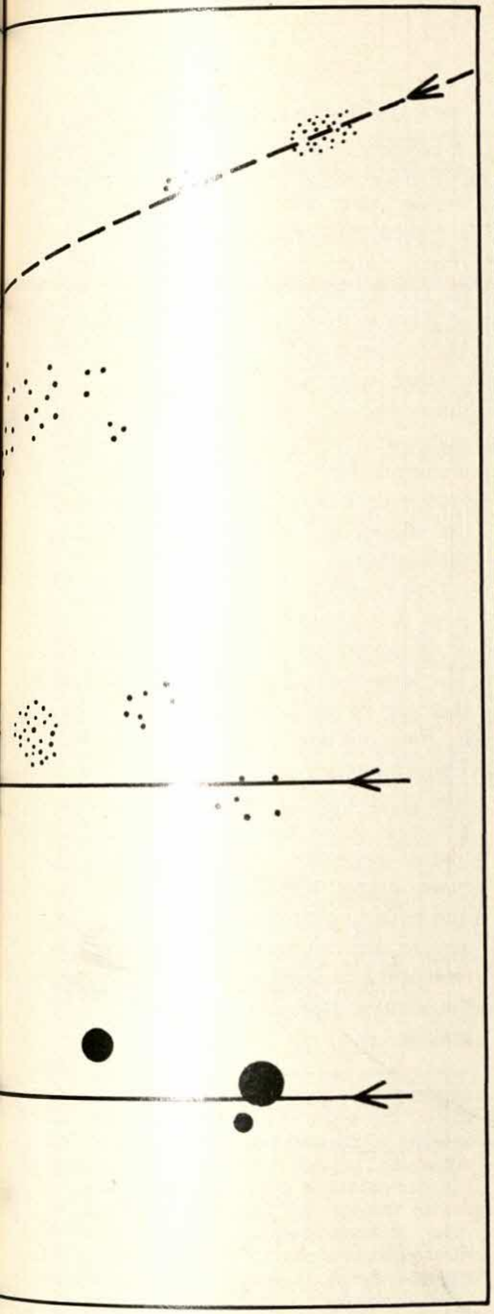
METEORITE SWARMS—Large meteorites often reach the Earth in swarms, or showers. Shown here are three examples. From the distribution of the elements collected, their point of departure was determined.

3

METEORITE CRATER—In historically ancient times (recent on a geological scale), a giant meteor fell on northern Arizona. The resultant crater is approximately 1.2 km (about 0.75 mi) in diameter and 182 m (about 600 feet) deep. The dimensions of the crater are dramatically illustrated by comparison with the large building that is barely visible at right.

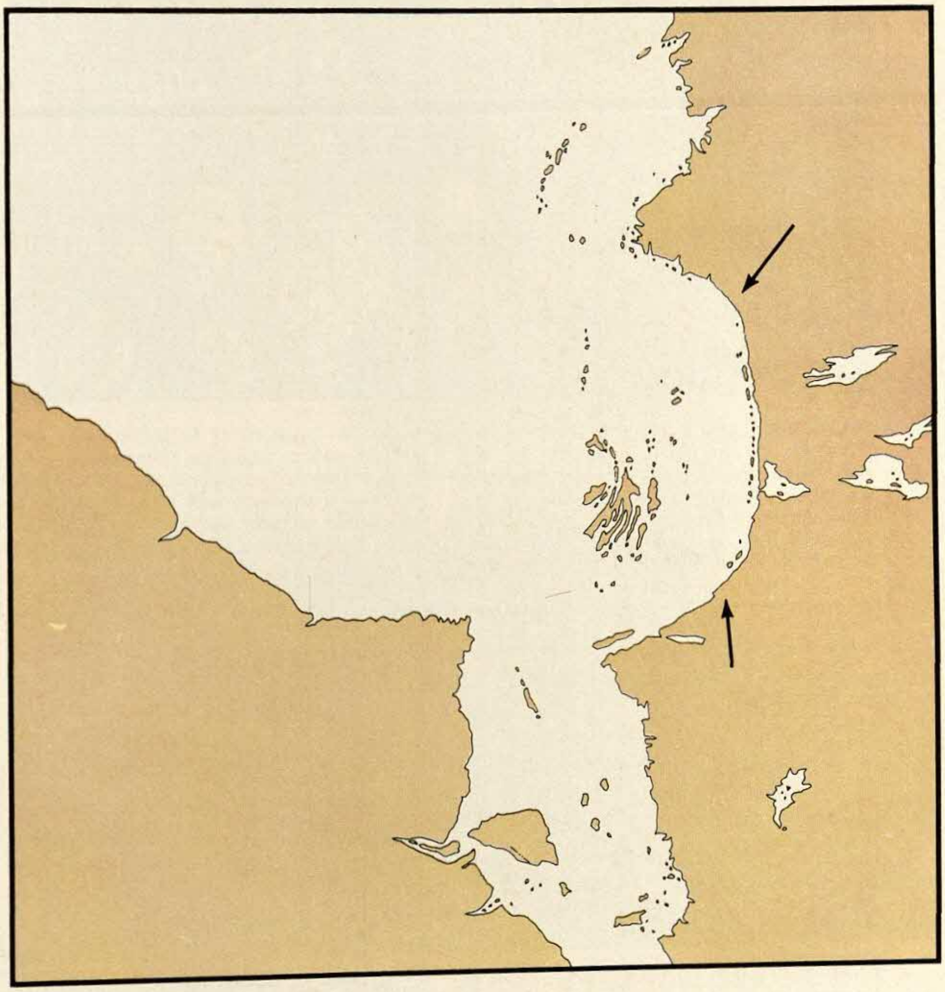
SIZE AND COMPOSITION OF METEORITES

Meteorites found on the Earth's surface vary widely in size, ranging from that of a small pea to such huge boulders as the 60-ton giant on the Hoba West Farm near Grootfontein, South West Africa. The composition of meteorites also varies. Some are rock fragments having a mineral structure vaguely resembling that of terrestrial rocks. Some consist mainly of iron, nickel, and cobalt, while others are of intermediate composition. Three main classifications exist: stone meteorites, iron meteorites, and stony irons. A fourth possible classification—the tektites—is still a puzzle to scientists, but is generally believed to be a strange form of meteorite. (Tektites, or glass meteorites, differ completely in appearance and composition from other types of meteorites. Because of this—and because their possible origin never has been definitely determined—a question still exists as to whether tektites



LARGEST METEORITE CRATER?—From a study of geologically recent and ancient meteorite craters, it has been suggested that Canada's Richmond Bay was probably formed 500 million or more years ago by a gigantic meteorite. Geological changes have obliterated most traces of the suspected impact. However, scientists believe that the structure of the bay clearly indicates that it is of an ancient meteoritic origin.

5



are terrestrial or extraterrestrial objects. Increasing evidence indicates, however, that they are the remains of much larger glassy lumps that have undergone erosion while traveling at high velocity through the Earth's atmosphere.)

All types of meteorites are quickly eroded by atmospheric agents when they reach the Earth's surface, and—except when they are of large size—eventually become difficult to recognize. Stone meteorites are most affected by such degeneration. After only a few years their appearance no longer reveals their extraterrestrial origin, except to an expert eye. The same degeneration occurs in the stony irons. It has been estimated that of the total number of meteorites that fall to the Earth, 93 percent are stones or stony irons, leaving the iron meteorites as a small minority.

Of the stone meteorites, 86 percent are further classified as chondrites. Chondrites have an internal structure of chondrules of different minerals, with silicates predominating. Such chondrules are not found in any Earth rock. Further subdivisions exist within this classification.

Scientists are attempting to establish the conditions under which the minerals found in meteorites were solidified and crystallized. Chemical analysis indicates that approximately 75 of the known elements are present in meteorites. Radioactive minerals have also been found in these missiles from space.

Analysis has confirmed that some meteorites are fragments of material cooled under high pressure comparable to that inside a planet, while others solidified by rapid cooling as soon as they formed.

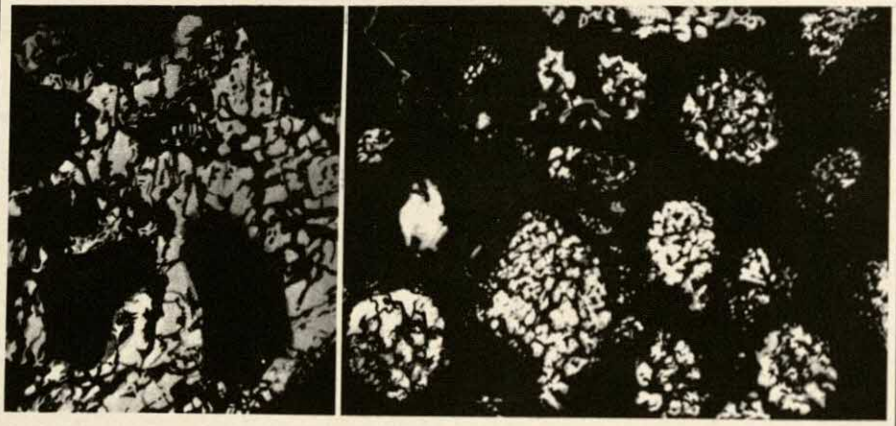
THE AGE OF METEORITES

The physicochemical analysis of meteorites did not begin until the end of World War II. Through techniques of radioactive analysis, five dates have been established, which are considered basic in the life of every meteorite. These dates are:

1. *Date of formation of the nuclei of the elements that form the meteorite.*
2. *Age in which the celestial body that was the origin of the meteorite was in a molten state.*
3. *Date of solidification of the celestial body of which the meteorite mass was a part.*
4. *Date of explosion of the parent body.*
5. *Date of the fall to Earth.*

6

a b



CHONDRITES AND INTERMEDIATE TYPES—Meteorites in which iron is not the predominant metal are rare on Earth because they are rapidly volatilized as they pass through the atmosphere and are subject to rapid erosion once they reach the ground. Illustrations 6a and 6b show thin sections of two such meteorites. Illustration 6a shows the light-colored mineral, tridymite, interspersed with black iron-nickel inclusions. (8 X) Illustration 6b shows a chondrite with small spherules of magnesium silicates and metallic nickel-iron, with a dark matrix of iron oxide. (12 X)

On the hypothesis that at the beginning of the solar system the abundance of elements and isotopes was the same everywhere, the presence in a meteorite of long-living radioactive isotopes and the absence of others of a shorter life-span indicate the date when these nuclei ceased their formation. To find this date, all radioactive elements in the meteorite must be analyzed.

In the process of radioactive decay, an element forms a new nucleus, which, in behavior and chemical makeup, differs from the original. When the celestial body that originally contained the meteorite material solidified, the parent element crystallized, and—after a certain period—the descendant nuclei that originated from the radioactive decay began to appear. Thus, from the ratio of parent abundance and descendant abundance, scientists can deduce the age at which the crystals were formed. Therefore, the period in which the parent celestial body was in a molten state, as well as the time of its solidification, can be determined.

Finally, when the celestial body broke up, the resultant meteorites immediately became subject to the bombardment of the cosmic rays present in space. Under the effects of this bombardment some of the nuclei of the meteorites began to undergo change. Thus, by determining the number of descendant elements formed in a meteorite by cosmic bombardment, it is possible to deduce how long a meteorite has remained in space without the protection of the external layers of its parent planet.

Moreover, if the nuclei generated by cosmic bombardment are also radioactive, the quantity of these in the meteorite at the time of analysis depends on two factors: how long these elements have remained in it while undergoing the process of decay, and the number of them produced by cosmic rays. Through consideration of these factors, the time spent by the meteorite on Earth after its fall can be accurately deduced.

METEORITE SCARS ON THE EARTH

In recent years a thorough study has been undertaken of all traces left on the Earth's surface by the impact of meteorites.

Meteorites generally fall on Earth in periodic showers, and numerous fragments of extremely small size have been found around the point of impact of larger meteorites. In many cases the fragments are parts of a larger meteorite; in other cases, it is probable that the secondary bodies traveled separately in space as part of a meteorite swarm.

Particular attention has been given to the search for craters that can be ascribed to geologically recent meteorite falls. Although historically ancient, the meteorite crater near Winslow, Arizona, is a typical example of such geologically recent craters. Approximately 30 meteorite craters have been discovered, some of them with diameters of more than 10 km (about 6 mi).

Once scientists had studied many of these craters, attention turned to the search for traces of geologically ancient meteorite falls—a difficult task because erosion on Earth tends gradually to mask the shapes and other characteristics of such craters.

Going back further and further into the past, it is obvious that only faint traces of the larger ancient craters still remain. The largest of all appears to be a crater that now forms the arc of Richmond Bay, in the southern part of Hudson Bay. This apparently ancient crater has a diameter of approximately 400 km (about 250 mi), a diameter vastly larger than that of any known crater of geologically recent origin. If research verifies the meteoritic origin of Richmond Bay, it may be said that the Earth has been struck by meteorites as large as those that formed the giant craters and seas on the lunar surface.

METEORITE DUST PARTICLES—The greater part of the mass of most meteorites that fall to Earth is dispersed in the atmosphere. This dispersion is the result of vaporization at high temperatures produced as the meteorite passes through the Earth's atmosphere. The vapor is condensed into small particles of vitreous substances (mixtures of oxides) of the type shown. The actual size of these particles is about 0.1 mm (about 0.004 in.).

7

DIFFUSE NEBULAS | nebulas, stellar clusters, and galaxies

The person who observes the sky on a clear night can see, among the stars, a few spots of diffused light that vary in size, brightness, and shape. Many more are visible with a telescope.

In the past these luminous patches of sky were all called nebulas. Today, astronomers recognize several different types of nebulas.

Some of the bright spots in the sky are clusters of stars located within the Milky Way, the galaxy to which the solar system belongs. Either because the stars are very close together or because the cluster is very far away, the stars cannot be individually resolved by the eye and they seem to fuse into a continuous luminosity. These bright spots are called stellar clusters. Other bright spots, that may look similar when seen through a low-powered telescope, are actually much larger and much farther away. These bright spots are entire star systems located far outside the limits of the Milky Way; they are called extragalactic nebulas or simply galaxies.

In still another class are the true or gaseous nebulas, also called diffuse nebulas. In these, tiny particles of matter are distributed in space like water droplets in the clouds of the Earth's atmosphere.

1

STUDYING NEBULAS—Because diffuse nebulas are not very bright, the best instruments for observing them are telescopes with large-diameter objectives and low magnification. In any case, the telescope does not reveal to the eye small details within the nebulas or their outer limits where the light fades away.

Photographs offer the best means of studying nebulas, but photographs, too, have their limitations. It must be remembered that the night sky is not completely dark but faintly luminous. In a photograph, diffuse nebulas that are only faintly luminous blend into this background and cannot be seen. Also, it is necessary to make extremely long time exposures, so that faint light sources will register on the photographic plate. In such a photograph, parts may be overexposed. The photographs seen here were taken with the most powerful telescopes in the world.

The Horsehead Nebula shown above is located between the stars ζ (zeta) and σ (sigma) in the constellation Orion. A dark nebula, it is a cloud of gas and dust so dense that it obscures bright stars beyond it. The shape of this dark cloud, somewhat resembling a horse's head, suggested the name given to the nebula. This photograph was made with the 200-in. Mount Palomar telescope.

DIFFUSE NEBULAS

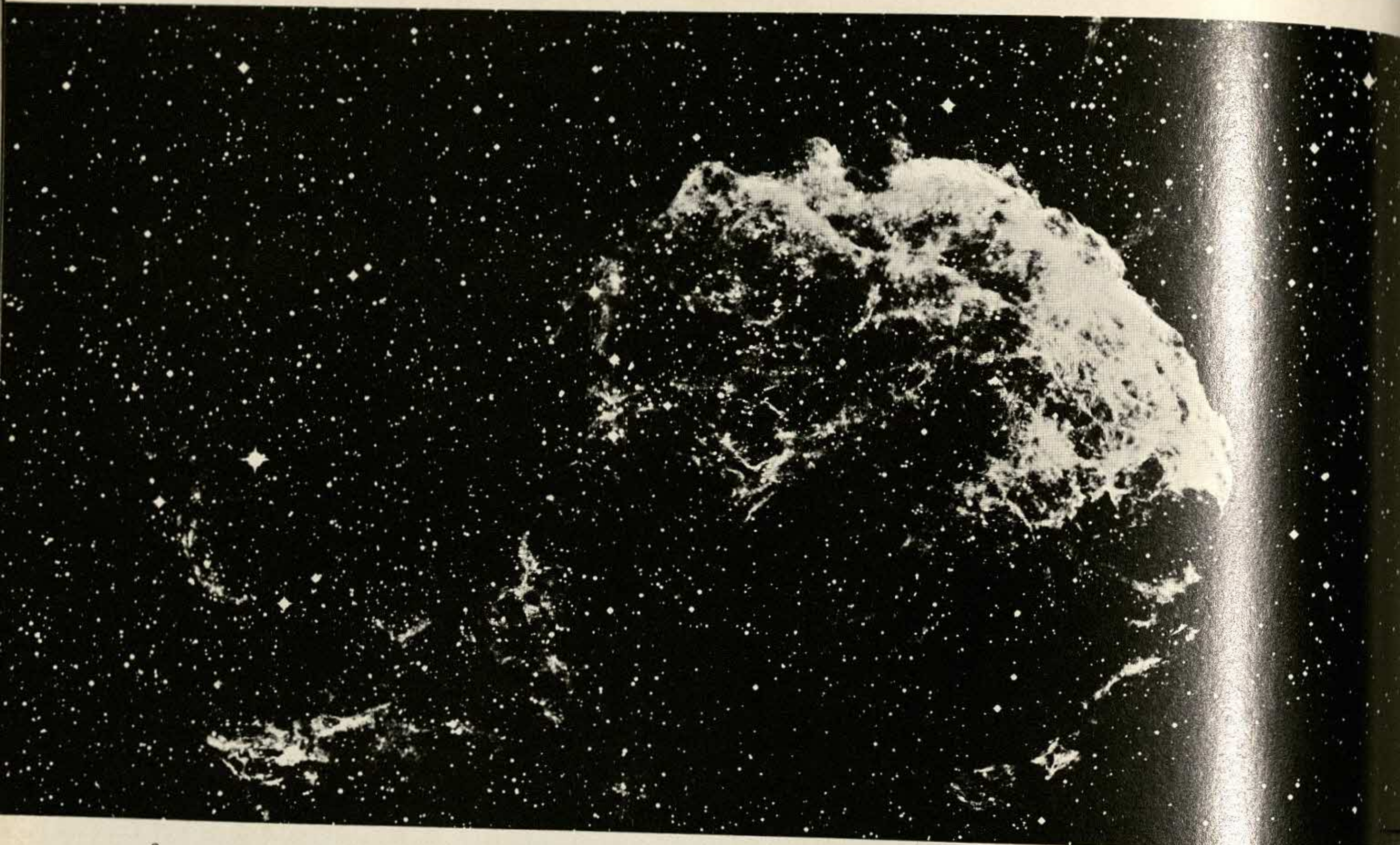
The space between the stars of a galaxy is not absolutely empty. It contains unevenly scattered atoms, molecules, and dust particles.

The element most common in interstellar space is hydrogen, which occurs at an average density of only one atom to many cubic centimeters of space. This corresponds to an extreme degree of rarefaction, considering that the Earth's atmosphere at sea level contains about 60 billion atoms per cubic centimeter. There are, however, local areas of greater density in interstellar space where 10 or even 100 atoms of hydrogen occur per cubic centimeter. In these areas, the gas is easily detected; it may even become visible as a diffuse nebula if bright stars nearby illuminate it.

Along with isolated atoms of gas, fine particles of dust are present in interstellar space. For the most part, the gas is hydrogen, with some helium and a very small percentage of other gases including oxygen. The exact composition of the dust is not known, but the dust scatters light, and when it is mixed with gas it can create an opaque cloud. Such a cloud appears as a dark nebula if it is between the Earth and bright stars. If, on the other hand, the cloud is behind or at one side of bright stars, it appears as a bright nebula when observed from the Earth.

Diffuse nebulas made up of gas and fine dust occur almost everywhere within the Milky Way. They are, however, most numerous near the galactic equatorial plane, where the stars are also most numerous.

2



3

4

MASS AND DENSITY OF NEBULAS—This is the Great Nebula in Orion which surrounds the star θ Orionis. The star cannot be seen in this photograph due to overexposure of the central part of the negative (Illustration 3).

It has been estimated that the Great Nebula in Orion is 10 light-years in diameter, and that its mass is equal to that of many stars the size of the sun. Although the mass of the nebula is great, the matter is spread over so large an area that the density is small, possibly 10^{-18} times that of the sun in the central part, and even less near the outer edges.

A STELLAR CATASTROPHE—Color photographs are not always of special value to astronomers. Too often, variations in luminosity within the field of the photograph make it impossible to render accurately the true colors of stars or nebulas. In some instances, however, color photographs show details that are not visible in black-and-white photographs.

This color photograph of the Crab Nebula in the constellation Taurus shows two distinct parts of the nebular structure: a diffuse cloud that appears blue-white, and radiating filaments that appear red. Studies show that the light from this nebula is polarized and that the plane of polarization varies considerably from one part to another, possibly because of a magnetic field that follows the pattern of the red filaments. The Crab Nebula is a strong source of both x-rays and radio waves.

The Crab Nebula is the result of a stellar catastrophe—the explosion of a supernova. Such a star may increase rapidly in luminosity, until it is bright as a billion ordinary stars, and then explode, scattering particles of matter into space, thus creating a nebula. Oriental astronomers witnessed the supernova that

WHY NEBULAS SHINE—Knowledge gained through spectroscopic study of the nebulas and the spectral classification of stars provides several facts concerning the source of nebular light.

The simplest case is that of a nebula composed entirely of dust. The dust grains simply reflect and diffuse light from nearby stars, or from stars actually immersed in the dust cloud. If the nebula is composed of hydrogen or helium gas, the phenomenon is more complex, but a rule applies. If the stars associated with the nebula are of the early stellar classes such as O or B (hot stars with surface temperatures higher than 15,000° C), ultraviolet radiation from these stars excites the gas in the nebula and causes it to emit radiation of longer wavelengths, or visible light. A spectroscopic examination of the light reveals the bright-line pattern typical of the gas.

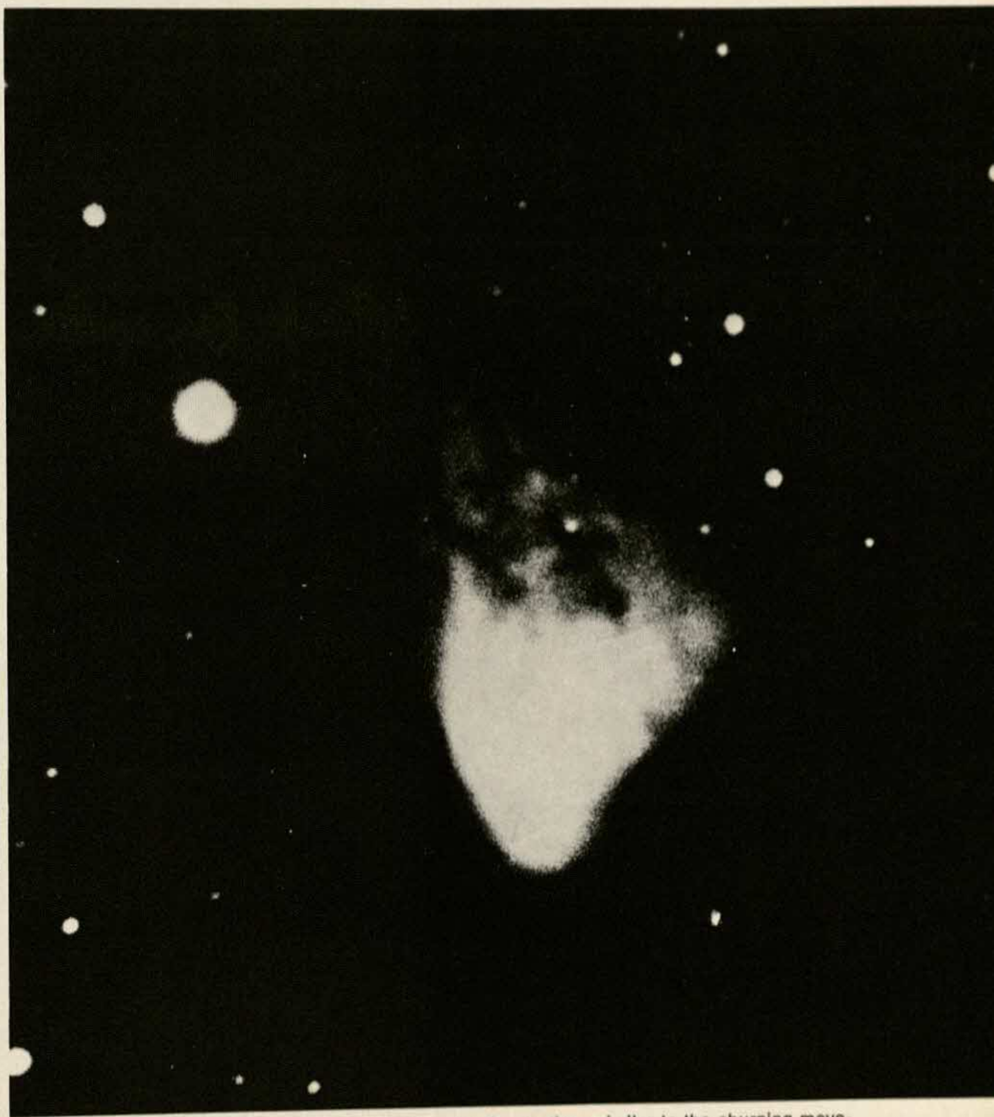
If, on the other hand, the stars associated with the gaseous nebula are of the intermediate or later spectral classes (cooler stars with surface temperatures below 15,000° C), the radiation emitted by the stars is not sufficient to make the gas fluoresce, and the gas merely reflects and diffuses the light of the stars. The spectrum is a continuous one with dark absorption lines, the same spectrum as that of the stars associated with the nebula.

Sometimes very hot "exciter" stars emit such a large fraction of their radiation in the ultraviolet range that they are almost invisible at visual wavelengths. In such a case it may appear, as in this photograph (Illustration 2) of Nebula IC 443 in the constellation Gemini, that the gaseous cloud is spontaneously luminous, although this is not the case.

The dimensions of diffuse nebulas are extremely variable. The smallest are always the planetary nebulas, gaseous envelopes surrounding single stars. Their diameters are less than one light-year. The dimensions of the larger diffuse nebulas are measured in tens of light-years.

If the luminous clouds that fill in the branching arms of the Milky Way are considered single diffuse nebulas, then the dimensions of the largest would be of the order of thousands of light-years.

5



A CHANGING NEBULA—Only a very few of the hundreds of nebulas that have been studied intensively show observable changes. One that does is Hubble's variable nebula. Observers who have studied the Doppler shift in the spectrum of nebular light believe that large turbulent motions may exist within the gaseous clouds—motions similar to the churning movement sometimes visible within atmospheric clouds. This turbulence could cause periodic changes in the shape or luminosity of a nebula; but if the nebula is very large and very far away from the Earth, the changes would rarely be observable.

created the Crab Nebula A.D. 1054; since that event this nebula has been constantly expanding at a rate estimated to be 1,000 km (about 600 mi) per second.

The light by which the Crab Nebula shines is not produced by either reflection or fluorescence as in the other nebulas discussed earlier. Instead, the light is emitted directly by electrons moving in a strong magnetic field at velocities close to the speed of light. This so-called synchrotron radiation is typically blue and highly polarized, just as observed in the diffuse cloud component of the Crab Nebula.

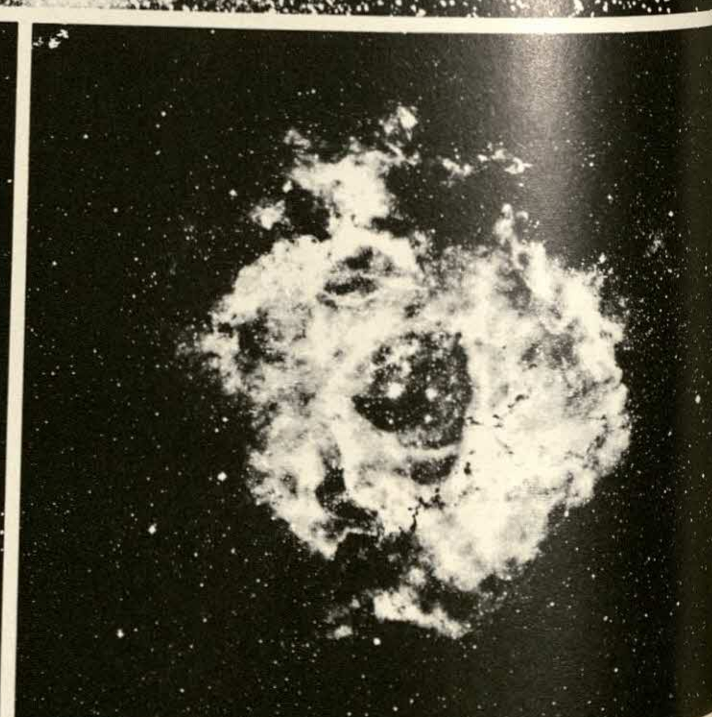
The energy required to keep the Crab Nebula shining is supplied by what must be one of the strangest objects in the universe—a neutron star. As the evolution of a star progresses, it gradually uses up the nuclear fuel that produces the heat required to support it against collapse. Without support the star contracts, and the end result in some cases is thought to be the incredibly dense matter in a neutron star. By some as yet poorly understood process (undoubtedly associated with a supernova explosion) the star assumes the final configuration of a sphere some 10 km (about 6 mi) across, composed almost entirely of neutrons. The neutrons are packed so tightly together that the star is supported by the nuclear repulsive force of the neutrons themselves. Ordinary matter (even in a white dwarf star) is mostly empty space between the nucleus and the electrons of individual atoms—but in the neutron star the densities must be about 10^{15} gm/cm^3. (The mean density of the Earth, in comparison, is 5.5 gm/cm^3 (about 0.8 lb/in.^{3}).

Theorists suggested more than 30 years ago that neutron stars might exist, but observational evidence was lacking until pulsars were discovered. Pulsars are celestial radio sources that emit bursts of radiation at regular intervals of from 0.03 to 4 seconds. They are associated with supernova remnants, and although the mechanism responsible for the radio emission is still unclear, most astronomers now agree that pulsars are rotating neutron stars. This view received support when a very fast pulsar was discovered in the center of the Crab Nebula. Furthermore, the central star was found to emit bursts of light at the same frequency as the pulsar, and since the central star is at the same position as the pulsar, the two must be identical. The central star of the Crab is the only optical pulsar known, probably because it is so young compared to other pulsars. In addition to being the fastest pulsar, the Crab pulsar is also slowing down. This spindown could release enough energy into the Crab Nebula itself to explain the continued synchrotron radiation.

While supernova remnants are relatively rare among nebulas taken at random, several others can be identified that have properties similar to the Crab Nebula. However, the others are all evidently older because they are larger and dimmer; and their associated pulsar (if present) is slower than the pulsar in the Crab Nebula.

6

7



8

DISCOVERING INVISIBLE NEBULAS—By comparing counts of the stars in different parts of the sky, astronomers can detect the presence of nebulas that are not clearly visible. Where the sky is clear of obscuring nebulosity, a count of stars of different magnitudes seen within a square degree of area of the sky can be plotted on a graph to show an increasing function, as in graph **a** (bottom right of Illustration 6). The fainter the stars counted, the more numerous they are. Where obscuration occurs there is a falling-off in the numbers of fainter stars counted, as in graph **a′**.

This photograph of the field of stars near the star ν Scorpionis reveals a nebula that is visible only in its central area, where it diffuses the light from several very bright stars. The nebula is actually a dust cloud extending far out in all directions from the luminous area; the cloud almost fills the photographic field. Star counts helped in establishing the approximate limits of this nebula.

THE OBSCURING POWER OF INTERSTELLAR DUST—To interpret the phenomenon observed in nebulas composed of fine dust, it is necessary to construct a theory of the obscuring power of interstellar dust.

Imagine a small cube of material with sides measuring one centimeter. When placed on a surface, the cube would cover one square centimeter of area. Now suppose the cube were perfectly divided into 1,000 cubes with sides measuring one millimeter. When placed side by side on a surface, these cubes would cover 1,000 mm²—that is, 10 cm², or 10 times the previous area. If the sides of the cubes measured one-tenth of a millimeter (comparable to the dimensions of fine sand), they would cover 100 cm², or one square decimeter. If the sides of the cubes measured one-hundredth of a millimeter (thick dust), they would cover 10 square decimeters. If the sides of the cubes measured one micron (fine dust) they would cover one square meter. If division were continued, however, the surface would no longer be covered because light rays would pass through the extremely small particles.

Some nebulas, such as that in the constellation Scutum (Illustration 7), are extremely large, even on an astronomical scale; but they are made up of dust grains of a size perfectly adapted to obscuring starlight. It has been estimated that one milligram of ordinary house dust per square centimeter of the cross section of a nebula would be enough to produce complete opacity; but the actual density of dust in the dark nebulas is believed to be somewhat greater than that.

THE BIRTH OF STARS—In the central part of the nebula NGC 2237 (Illustration 8) in the constellation Monoceros are dark spots that are extremely dense clouds of gas. They appear dark because they are too dense to transmit the light from stars. It has been hypothesized that new stars are being formed, by a process of condensation, within these dark nebular clouds. When the gas becomes dense enough, thermonuclear reactions are triggered, and the new star becomes luminous.

A two-way exchange of matter may take place between stars and the nebulas near them. At times stars may throw off large amounts of matter, just as a comet throws out material in the form of a glowing tail. This matter adds to the density of the nebula. At other times, material in the nebular cloud may go into the formation of new stars, so that the nebula may, in time, destroy itself.

Diffuse nebulas are sources of radio waves, and many of them have been detected with radio telescopes. The emission of radio waves is due chiefly to atomic processes of heating and ionization taking place within the nebulas.

Diffuse nebulas have been widely studied in recent years, and much new knowledge has been gained since very large telescopes, such as the 200-in. Hale reflector at Palomar Observatory, came into use. Perhaps the best known of the diffuse nebulas is the Great Nebula in the constellation Orion. This nebula is bright enough to be visible to the unaided eye.

THE PLEIADES—Astronomers have known for a long time that the Pleiades (a cluster of stars in the constellation Taurus) is surrounded by nebulosity; but only in recent years, since large telescopes came into use, has it been possible to study this nebula in detail. Part of the nebula is visible because it diffuses light from very bright stars; the existence of another part has been theorized through a statistical count of the background stars.

An interesting point is that light diffused by this nebula is polarized, while light from the stars themselves is not. This indicates that the dust particles making up the nebular cloud are elongated and oriented with the major axis in the same direction. This would seem to be possible only if the particles respond in some way to a magnetic field existing within the Pleiades cluster.

GALAXIES | giant aggregates of stars

After Galileo had begun using the telescope for astronomical research and larger and more powerful telescopes had been built, many astronomers devoted themselves to a systematic exploration of the entire celestial sphere. They saw that all the celestial objects they observed besides the sun, the moon, and the planets, could be classified in two broad categories: objects that appeared as point sources of light such as the stars, and objects with appreciable dimensions called nebulas.

The use of telescopes constructed in the eighteenth and nineteenth centuries led to the discovery of many nebular objects, among which two important categories were distinguished. Certain nebulas, when observed through a sufficiently powerful telescope, were seen to be clusters of stars; others, on the other hand, seemed to be fairly similar to terrestrial clouds, and this led to the belief that such nebulas were composed of gas. The first type were called resolvable nebulas, and the second irresolvable nebulas.

Subclassification was somewhat arbitrary, since there was no criterion for establishing whether an apparently irresolvable nebula would not, in fact, be resolvable, if it could be observed with a telescope that was powerful enough.

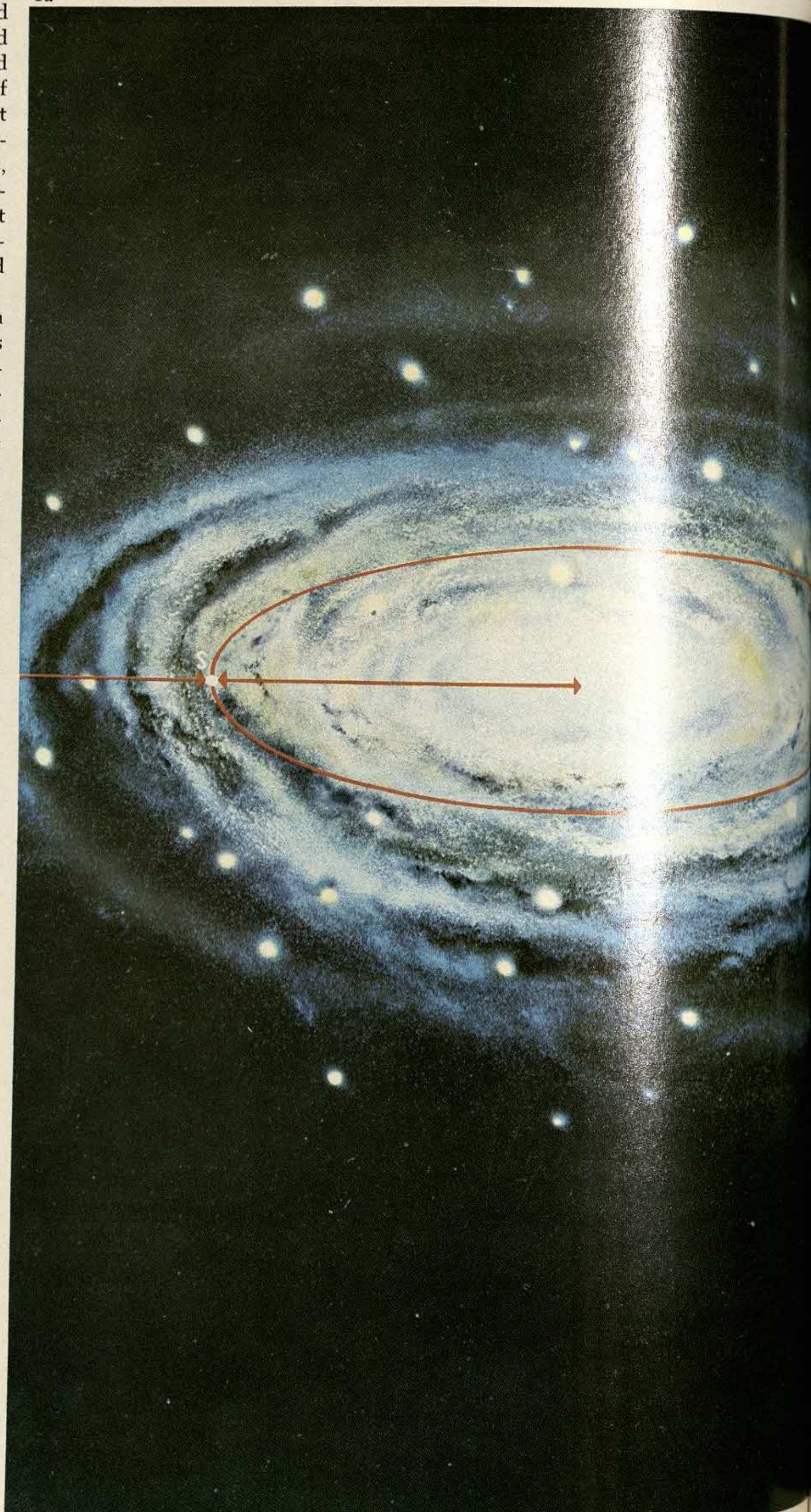
In the present century very important advances have been made. Spectroscopic analysis has made it possible to establish, without the use of a large telescope, which of the nebulas are composed of gas uniformly diffused in space, and which consist of a cluster of stars. Moreover, astronomers learned how to measure the distance of nebulas, no matter how distant they were.

EXTRAGALACTIC SPACE

Although no stars outside the limits of the Galaxy can be observed directly, not all space external to the Galaxy is empty. (When capitalized, the word *Galaxy* refers to the galaxy to which the solar system belongs—the Milky Way.) At distances on the order of ten times the diameter of the Galaxy—distances corresponding to about one million light-years—are other galaxies of different shapes.

Like the Milky Way, each of these galaxies consists of stars numbering hundreds of billions. When the distance of these objects was determined, they were

1a



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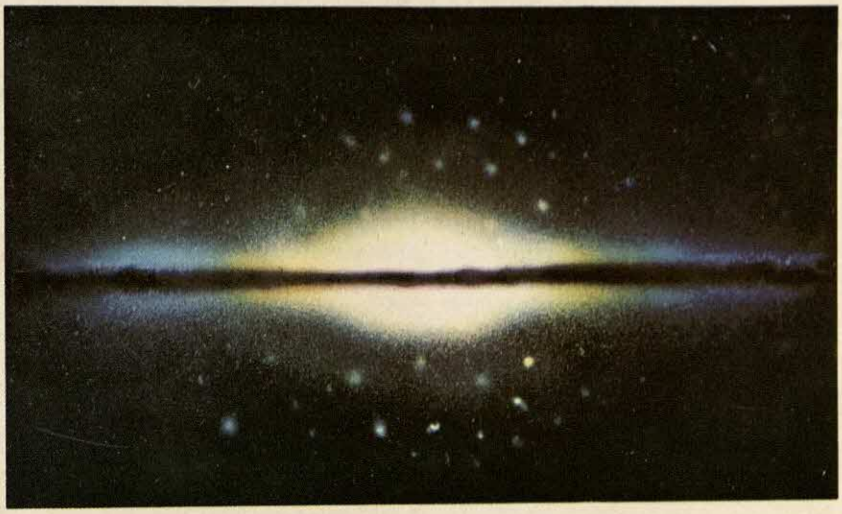


THE GALAXY—Illustration 1a shows the constitution of the Milky Way. The space surrounding the sun is occupied by other stars. These stars are not very close to one another. In fact, they are separated to such an extent that the light of a star reaches its neighbors after a passage through space of several years at a speed of 300,000 km/sec (about 186,000 mi/sec).

The number of stars, however, is very much greater within the lens-shaped core or inner part of the galaxy. The diameter of this densely populated area is about a hundred thousand light-years. Its maximum thickness is only about a tenth of its diameter (Illustration 1b). The sun is located at the periphery of this lens-shaped area, which contains about 100 billion stars. Looking toward the plane of the galaxy, an observer sees the luminous streaks known as the Milky Way. Looking, on the other hand, in a direction perpendicular to that of the Milky Way, very few stars are visible.

In addition to the stars, the Galaxy contains vast quantities of diffuse matter in the form of gas and fine dust. This material is most densely distributed close to the plane of the Galaxy. The luminous areas of appreciable size that surround the lenticular structure of the Galaxy are groups of thousands of stars each, and are known as globular clusters.

called extragalactic nebulas. When their true nature was recognized, they became known as galaxies.

Extragalactic space, that is, space outside the Milky Way, is studded with galaxies. The space between them is practically empty and thus permits their telescopic observation. The most powerful optical telescopes have detected galaxies so distant that their light takes two billion years to reach the Earth.

GALACTIC ROTATION

Galaxies are composed of stars, of transparent gas clouds in the atomic state, and of opaque clouds of fine dust distributed in between. The total amount of matter condensed in the stars and dispersed between them has considerable mass and is self-attractive. The stars would collide if they did not rotate around the center of the nebular mass. Just as the Earth and the planets revolve around the sun, so the stars that form a galaxy rotate around the center of the galaxy.

The Milky Way has a lenslike structure with groups of stars (called globular clusters) situated outside the disk-shaped central portion. Scientists have determined the velocity of galactic rotation by spectroscopically analyzing the light from two opposite extremes of the Galaxy. They have found that the rotational speed is greatest in the highly flattened disk and least in the nearly spherical systems of the globular clusters. The globular clusters show a systematic drift of velocity of about 250 km/sec (155 mi/sec) toward the constellation Carina. This can best be understood in terms of concentric spheroidal subsystems, with increases in rotational speed and degree of flattening occurring from one subsystem to the next.

In the inner portion of the galaxy, where most of the mass is concentrated, the system rotates more or less like a rigid body. In the outer part of the disk, however, where the sun and most of the visible stars are located, the angular velocity diminishes outward from the center—just as it does with planets in the solar system.

If an observer considers a group of stars surrounding the solar system, he will find those located between the solar system and the center of the galaxy gaining on the solar system. Moreover, he will find those farther away from the center lagging behind. In other words, both the stars that are nearer the center of the galaxy, but ahead of the solar system, and the stars that are farther away from the galactic center, but behind the solar system, exhibit a systematic velocity of recession when their velocity in line of sight is measured. On the other hand, both the stars that are nearer the center and behind the solar system and those that are farther out and ahead of the solar system show a systematic velocity of approach.

For distances up to about 2,500 parsecs or 8,150 light-years (1 parsec = 3.26 light-years), this effect of differential galactic rotation increases uniformly with distance in those directions where the effect is at its maximum. The effect, therefore, is most readily observed from the spectra of distant stars; for the nearer stars the effect is somewhat obscured by the presence of random velocities, which result from the fact that galactic orbits are not exactly circular.

Another effect of differential rotation is noticeable in stellar proper motions—apparent changes in the positions of the stars—with a maximum effect in the directions at right angles to the galactic plane. This effect is independent of distance and corresponds to an average proper motion of about 0.21 seconds of arc per century, which in turn corresponds to a velocity of 10 km/sec/1,000 parsecs (about 6 mi/sec/1,000 parsecs).

Studies of the magnitudes of the effects in proper motion and radial velocity indicate that the sun orbits around the galactic center at a speed of about 250 km/sec (155 mi/sec). Consequently, the sun completes its orbit around the center of the Milky Way in about 200 million years.

MASS AND DENSITY

From the speed of galactic rotation, scientists have been able to estimate the approximate mass of the Galaxy at about 150 billion times the mass of the sun. They have also been able to estimate the density of the material in the neighborhood of the sun by computing the velocities perpendicular to the galactic plane and by assuming a condition of statistical equilibrium. Several studies have indicated that the density of material in the solar neighborhood is about 0.1 of the mass of the sun per cubic parsec. The known stars account for about 60 percent of this material; interstellar matter accounts for an additional 20 percent; and unobserved material may account for the remainder.

The stars that make up galaxies have, on the average, the same mass as the sun. Once the total mass of the galaxy has been determined, the number of stars contained in it can be estimated.

ELLIPTICAL AND SPIRAL FORMS

Observations and calculations such as these have brought out the fact that most galaxies have a mass equal to that of the Milky Way and, therefore, contain a similar number of stars. The fact that all galaxies rotate helps to explain why many galaxies have spiral structures. Just as the planets farthest from the sun rotate around it more slowly than those closest to it, so the stars most distant from a galactic center rotate more slowly than the stars closer to the center of the galaxy. If the galaxy had an irregular shape at the time of its formation, and plenty of gas and dust was available for star formation, the nature of the spiral arms was determined by the differential rotation—plus as yet uncertain magnetic effects. The gas and dust are concentrated in the arms, and star formation continues here. As a galaxy ages, its spiral structure becomes less pronounced as random motion of stars moves them from the region of their formation. Finally, the older galaxies may already have undergone such a high degree of rotation and random motion that their original spiral structure has become completely obliterated and they now appear in a homogeneous elliptical form.

THE COMPONENTS OF GALAXIES

The Milky Way is made up of a large variety of objects such as giant stars and dwarf stars, hot stars and cold stars, dense clusters of stars and sparse clusters of stars, double stars and multiple stars, dense stars and rarefied stars, clouds of fine dust and clouds of gas (some luminous, others dark), remains of exploded stars, and so forth. Other galaxies also contain a variety of objects, but none of these can be identified as readily as those at a lesser distance in the Milky Way.

Perhaps one billion galaxies are within range of the 200-in. Hale telescope on Mount Palomar, and several thousand of them are close enough to reveal their structural details. Galaxies vary greatly in appearance. About 2 to 3 percent of them have a chaotic, mottled appearance; the two Magellanic Clouds observable in the southern sky are examples of these so-called irregular galaxies. The elliptical galaxies, which are perfectly smooth and symmetrical systems, make up about 20 percent of the total number of galaxies; these galaxies show no trace of interstellar dust or gas, and they have no young blue stars. The great majority of galaxies, however, show some evidence of the spiral structure that typifies both our own galaxy, the Milky Way, and the galaxy M31 in the constellation Andromeda.

The great spiral M31 is one of the closer galaxies, less than two million light-years away. Within the galaxy are hundreds of star clusters and many diffuse nebulas. The most significant observation, however, is that concerning the distribution of stellar populations. Certain regions of space are occupied mostly by young stars—that is, stars whose ages are measured in millions rather than billions of years, as in the case of old stars. These young stars are quite luminous and are interspersed with large amounts of interstellar matter—either gaseous or in the form of fine dust. Such regions are called Population I regions. Other regions of space are occupied mostly by old stars. These are only weakly luminous, predominantly yellow or red, and are uniformly distributed. Little diffuse matter is present between these stars, and such regions—are called Population II regions.

The composition of a galaxy in terms of its stellar populations is roughly indicative of the age of the galaxy itself. Elliptical galaxies are composed chiefly of Population II regions, while regular-shaped galaxies are composed chiefly of Population I regions. The peripheral parts of spiral galaxies are composed of Population I regions, but their central parts consist of Population II regions.

THE ILLUSTRATED SCIENCE DICTIONARY

Equatorial Telescope to Free Fall

KEY TO PRONUNCIATION

The diacritical marks are:

ə	b*a*nan*a*, *a*but	e	b*e*t	th	*th*in
ᵊ	preceding l, m, n as in battl*e*	ē	b*ea*t	t͟h	*th*en
ə̇	*e*lectric	i	t*i*p	ü	r*u*le, f*oo*l
ər	f*ur*ther	ī	b*i*te	u̇	p*u*ll, w*oo*d
a	m*a*t	j	*j*ob, gem	ue	German h*ü*bsch
ā	d*ay*	ŋ	si*ng*	u̅e̅	French r*ue*
ä	c*o*t, f*a*ther	ō	b*o*ne	yü	*u*nion
au̇	n*ow*, *ou*t	ȯ	s*aw*, *a*ll	zh	vi*si*on
		ȯi	c*oi*n		

ˈ mark preceding the syllable with strongest stress.
ˌ mark preceding a syllable with secondary stress.

equatorial telescope \ˌē-kwə-'tōr-ē-əl 'tel-ə-ˌskōp\
ASTRONOMY. A telescope specially mounted so that it automatically turns, when adjusted, to track any celestial body. The device compensates for the earth's rotation by turning opposite to, and at the same speed as, the earth's rotation.

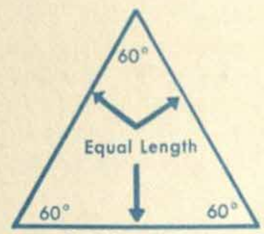
An EQUATORIAL TELESCOPE *is used to make time-exposure photographs of a star field.*

Mt. Palomar Observatory, Cal.

EQUATORIAL TELESCOPE

equilateral \ˌē-kwə-'lat-ə-rəl*adj.*
MATHEMATICS. Having sides that are of equal length.

A rhombus is an EQUILATERAL *polygon of four sides.*



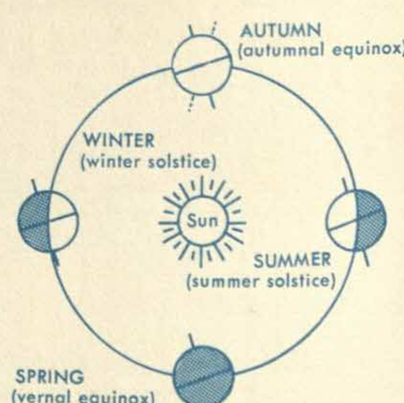
EQUILATERAL

equilibrium \ˌē-kwə-'lib-rē-əm\ *n.*
1. CHEMISTRY. A condition in a reversible reaction in which the velocities of the two opposing chemical reactions are equal, and the system does not change chemically. 2. PHYSICS. The state of a body at rest, or in motion with constant velocity. 3. PHYSIOLOGY. The condition of the body in which materials taken in are balanced by excretions.

Chemical EQUILIBRIUM *can be disturbed by a change in temperature or pressure.*

equinox \'ē-kwə-ˌnäks\ *n.*
ASTRONOMY. The two times of the year (approximately March 21 and September 23) when the sun appears directly overhead to an observer on the earth's equator and when nights and days are of equal length everywhere on earth.

The vernal EQUINOX *marks the beginning of spring.*



EQUINOX

equivalent \i-'kwiv-ə-lənt\ *n.*
1. CHEMISTRY. The atomic weight of an element divided by its valence in a given chemical reaction; also, the weight of an element that combines with 7.999 grams of oxygen or 1.00797 grams of hydrogen. 2. MATHEMATICS. A statement or proposition that can be substituted for another statement or proposition.

The EQUIVALENT *of an element may be measured in grams or in other specified units of weight.*

era \'i(ə)r-ə *or* 'er-ə\ *n.*
EARTH SCIENCE. Any of the five principal divisions of geologic time, each of which includes one or more periods.

The Mesozoic ERA *is sometimes referred to as the Age of Reptiles.*


EROSION

erg \'ərg\ *n.*
1. PHYSICS. A unit of energy equal to the work done when a force of one dyne moves an object one centimeter. 2. EARTH SCIENCE. A desert area of shifting sand.

The ERG *is so small that the joule, equal to ten million ergs, is commonly used to measure quantities of energy.*

erosion \i-'rō-zhən\ *n.*
EARTH SCIENCE. The wearing away of rocks and other substances at the earth's surface by such natural agents as water, wind, waves and glaciers.

The control of EROSION *is important in the conservation of soil as a natural resource.*

ergot \'ər-gət\ *n.*
BOTANY and MEDICINE. A poisonous fungus that attacks the rye plant, forming a horn-shaped moss that replaces the grains and stops their growth.

ERGOT *is used medicinally to stop some kinds of bleeding.*


ESCARPMENT

erythrocyte \i-'rith-rə-ˌsīt\ *n.*
ANATOMY and ZOOLOGY. A red blood corpuscle.

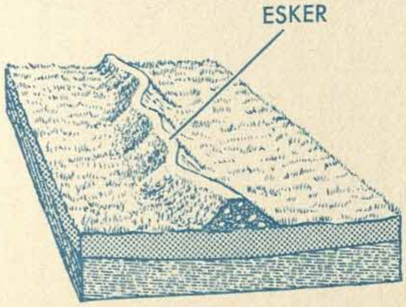
An ERYTHROCYTE *contains hemoglobin.*

escape velocity \is-'kāp və-'läs-ət-ē\
ASTRONAUTICS. The velocity necessary for an object to escape, without further propulsion, from the surface of a planet or other body.

The ESCAPE VELOCITY *of a rocket launched from the earth is approximately 25,000 miles per hour, or 7 miles per second.*

escarpment \is-'kärp-mənt\ *n.*
EARTH SCIENCE. A long cliff or ridge that separates two comparatively level surfaces; also, a steep slope dividing two gently-sloping surfaces.

An ESCARPMENT *may be a result of erosion or faulting.*



esker \'es-kər\ *n.*
EARTH SCIENCE. A long, irregular ridge of crudely-stratified, or layered, sand and gravel, created by streams flowing in and under glaciers.

An ESKER *is found only in areas once covered by a continental glacier.*

esophagus \i-'säf-ə-gəs\ *n.*

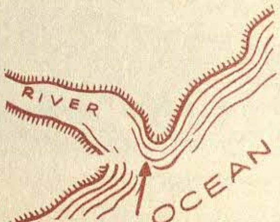
ANATOMY. The gullet, or muscular tube, that connects the mouth, or pharynx, with the stomach.

The muscles of the ESOPHAGUS *propel food through it and into the stomach by successive contractions called peristalsis.*

ester \'es-tər\ *n.*

CHEMISTRY. A compound that results from the reaction between an acid and an alcohol and that usually has a pleasant odor.

One well-known ESTER *is butyl acetate, often used as a solvent for fingernail polish.*



ESTUARY

esterification \e-ˌster-ə-fə-'kā-shən\ *n.*

CHEMISTRY. The creation or production of an ester.

An acid catalyst is usually used in ESTERIFICATION.

estivate \'es-tə-ˌvāt\ *v.*

ZOOLOGY. To remain inactive during the hot season, as do some mammals, reptiles, amphibians and insects; also spelled aestivate.

When animals ESTIVATE, *their food requirements are lowered.*

estrogen \'es-trə-jən\ *n.*

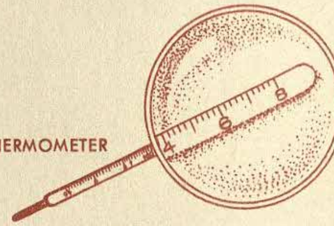
PHYSIOLOGY. Any female hormone that controls the development of secondary sex characteristics.

ESTROGEN *is secreted by specialized cells within the ovaries.*

estuary \'es(h)-chə-ˌwer-ē\ *n.*

EARTH SCIENCE. A long, narrow bay resulting when the sea enters the mouth of a river and fills valley depressions; also, a bay at the mouth of a river in which tides and river currents intermingle.

The mouth and harbor area of New York's Hudson River is an ESTUARY.



ETCHING

etching \'ech-iŋ\ *n.*

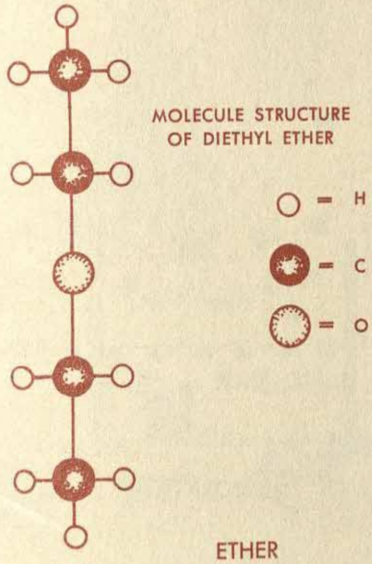
CHEMISTRY. The chemical reaction of a glass or metallic object with an acid, the object having been previously coated with an acid-resistant substance. Markings cut through the coating expose the surface to the action of the acid, resulting in a figured surface.

Thermometer scale ETCHING *is produced by the action of hydrofluoric acid.*

ether \'ē-thər\ *n.*

1. CHEMISTRY. A general name for a class of compounds prepared by dehydrating an alcohol with a strong dehydrating agent, such as sulfuric acid; also, a common name for diethyl ether, $C_2H_5OC_2H_5$, a colorless, volatile, highly-flammable compound. 2. PHYSICS. An imaginary fluid, transparent and nonviscous, that was once assumed to fill all space and act as a medium for the propagation of light.

Diethyl ETHER *is used as a solvent in industry and as an anesthetic before surgery.*



ETHER

ethylene glycol \'eth-ə-,lēn 'glī-,kȯl\

CHEMISTRY. $C_2H_4(OH)_2$. The simplest polyhydric alcohol, produced from ethylene by the addition of two hydroxyl groups.

Because of its lower vapor pressure and low freezing point, ETHYLENE GLYCOL *is used in antifreeze solutions for automobile radiators.*

Euclidean \yu̇-'klid-ē-ən\ *adj.*

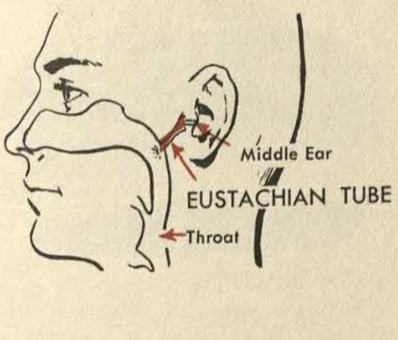
MATHEMATICS. Referring to the geometry based on the axioms of Euclid; also, referring to other mathematical concepts appearing in the works of Euclid, as the Euclidean algorithm.

The principles of ELUCIDEAN *geometry are contained in Euclid's "Elements."*

eudiometer \,yüd-ē-'äm-ət-ər\ *n.*

CHEMISTRY. A graduated glass tube used to measure and analyze gases.

Gas in a EUDIOMETER *is exploded by the use of an electric spark.*



eugenics \yu̇-'jen-iks\ *n.*

BIOLOGY. The science based on human heredity that suggests methods for improving the human race through the control of social and biological factors.

The study of EUGENICS *has resulted in the development of state laws governing the treatment of mentally-defective people.*

Eustachian tube \yu̇-'stā-shən 't(y)üb\

ANATOMY. The bony tube or duct that connects the middle ear to the throat, creating uniform air pressure on both sides of the eardrum.

The EUSTACHIAN TUBE *in man develops from an embryonic gill slit.*

euthenics \yu̇-'then-iks\ *n.*

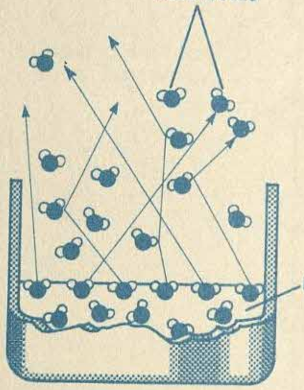
A science that seeks improvement of human well-being through improvement of environmental conditions.

It is hoped that the practice of EUTHENICS *will result in more efficient and better-functioning human beings.*

evaporate \i-'vap-ə-ˌrāt\ *v.*

CHEMISTRY and PHYSICS. To change from a liquid to a gas.

Ethyl alcohol will EVAPORATE *more quickly than water.*



EVAPORATE

evection \i-'vek-shən\ *n.*

1. ASTRONOMY. An irregularity in the moon's motion in orbit, due to the attraction of the sun. 2. BOTANY. In certain algae and fungi having a series of attached cells, the position at the base of a new branch in relation to the parent cell which appears to result in the branch dividing into two parts.

The EVECTION *of the moon sometimes affects the time of an eclipse.*

even function \'ē-vən 'fəŋ(k)-shən\

MATHEMATICS. A function whose graph is symmetrical with respect to the vertical or y-axis; also, a function whose value is unchanged when the sign of a number in the domain of the function is changed, such as $f(-x) = f(x)$ for all x in the domain of f.

The function defined by the equation $f(x) = x^2$ *is an* EVEN FUNCTION.

evening star \'ēv-niŋ 'stär\

ASTRONOMY. Any visible planet that sets after the sun; a name often applied to Venus.

It is possible to see Mercury as an EVENING STAR *when it is at its greatest elongation.*

even parity \'ē-vən 'par-ət-ē\

ENGINEERING and MATHEMATICS. A method of representing and interpreting computer data, where each valid character contains an even number of binary digits in the "on" condition; see *odd parity*.

When computer data is stored in EVEN PARITY *on magnetic tape, one of the channels on the tape serves as a check to determine whether or not conditions of even parity have been met on the other six channels.*

EVERGREEN

evergreen \'ev-ər-ˌgrēn\ *n.*

BOTANY. A tree or other plant that does not lose its leaves seasonally, as do deciduous plants.

An EVERGREEN *loses and replaces leaves unnoticeably throughout the year.*

evolution \ˌev-ə-'lü-shən\ *n.*

1. BIOLOGY. The continuous process of the development of a species from its earliest stages of life. 2. MATHEMATICS. The process of finding the root of a number.

The names of Jean Lamarck and Charles Darwin are associated with the early study of EVOLUTION.

EVOLUTION

excitation \ˌek-ˌsī-'tā-shən\ *n.*

1. PHYSICS. The creation of a magnetic field by a current for use in an electrical generator; also, the process of raising the energy level of an atomic nucleus, following which a particle of some kind is usually given off. 2. CHEMISTRY. The energizing of an atom, usually by moving an electron into a higher energy level.

EXCITATION *of an electrical generator is often provided by feeding back a portion of the current produced.*

excretion \ek-'skrē-shən\ *n.*

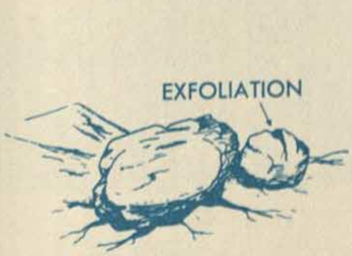
BIOLOGY and PHYSIOLOGY. Elimination of waste substances by an organism, as carbon dioxide given off by respiring animal and plant cells or the protein waste urea, extracted from the blood by the kidneys and eliminated by the bladder.

The EXCRETION *of water in man occurs partially through the sweat glands of the skin.*

exfoliation \(ˌ)eks-ˌfō-lē-'ā-shən\ *n.*

EARTH SCIENCE. A weathering process in which rock surfaces break or peel off in a series of circular shells as a result of physical or chemical action.

One form of EXFOLIATION *occurs when water seeps into cracks in a rock and freezes.*



exhaustion \ig-'zȯs-chən\ *n.*

PHYSIOLOGY. A condition of utmost fatigue or weakness.

Rest and food can overcome physical EXHAUSTION.

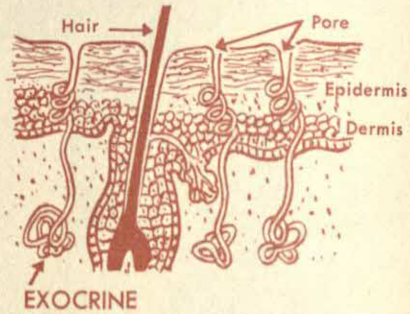
exhaust velocity \ig-'zȯst və-'läs-ət-ē\

AERONAUTICS and ASTRONAUTICS. The speed of gases expelled from the combustion chamber of a rocket or jet.

Long-range rockets have high EXHAUST VELOCITY.

exocrine \'ek-sə-krən\ *adj.*
ANATOMY. Referring to a gland that discharges its secretions into a duct.

The pancreas is an EXOCRINE *gland.*



EXOCRINE
Sweat Gland

exoskeleton \ˌek-(ˌ)sō-'skel-ət-ᵊn\ *n.*
ZOOLOGY. The hard, external framework or supporting covering of an animal.

The shell of a lobster is an EXOSKELETON.

exosphere \'ek-sō-ˌsfi(ə)r\ *n.*
EARTH SCIENCE. The outer part of the earth's atmosphere that lies beyond the ionsphere and begins at an altitude of 200 miles or more.

Recent knowledge about the EXOSPHERE *has been obtained by the use of rockets and satellites.*

exothermic \ˌek-sō-'thər-mik\ *adj.*
CHEMISTRY. Referring to a chemical reaction in which heat energy is released.

A forest fire is an EXOTHERMIC *reaction.*

EXOSKELETON
Lobster

exotoxin \ˌek-sō-'täk-sən\ *n.*
BIOLOGY and MEDICINE. A poisonous substance excreted by some mircoorganisms.

The bacteria causing scarlet fever excrete an EXOTOXIN *from their cell bodies.*

expanding universe \ik-'spand-iŋ 'yü-nə-ˌvərs\
ASTRONOMY. A theory that all galaxies in the universe are constantly moving away from each other at great speed. The theory is based on observations indicating that all galaxies are moving farther away from the earth.

The theory of the EXPANDING UNIVERSE *has influenced research on the characteristics of the universe and of space.*

expansion \ik-'span-chən\ *n.*
1. PHYSICS. An increase in size or volume of a given mass, such as a solid or a gas, caused generally by the addition of heat to, or the reduction of pressure on, a confined quantity of gas. 2. MATHEMATICS. In algebra, the detailed expression, term by term, of a mathematical quantity that may have been originally expressed in a simplified form, such as a power of a polynominal, the product of polynominals or as a determinant.

Because pyrex glass has a coefficient of EXPANSION *only one-third that of ordinary glass, it can be subjected to much greater temperature changes without breaking than can ordinary glass.*


EXOTHERMIC
FOREST FIRE

experiment \ik-'sper-ə-mənt\ *n.*
A series of planned steps performed to test a hypothesis, solve a problem or discover new information.

Exactness, safety and neatness are three important considerations in conducting a chemical EXPERIMENT.

expiration \ˌek-spə-'rā-shən\ *n.*
PHYSIOLOGY and ZOOLOGY. The act of breathing out, or the escape of air through the nose or mouth.

Swimmers must learn to control inhalation and EXPIRATION.

explosion \ik-'splō-zhən\ *n.*
CHEMISTRY and PHYSICS. A rapid increase of pressure in a closed space, as in an exothermic chemical reaction, accompanied by a sudden release of large quantities of gas; also, the sudden release of a gas under great fluid pressure, or the noise produced by such release.

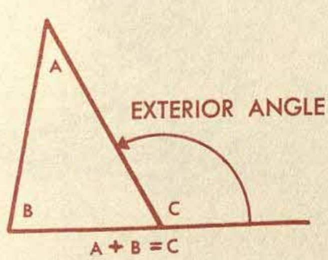
A chemical EXPLOSION *is often an extremely-rapid oxidation reaction.*

exponent \ik-'spō-nənt\ *n.*
MATHEMATICS. A number or symbol placed above and to the right of another number or symbol called the base. A positive exponent tells how many times the base is to be used as a factor.

In the expression y^4, which means (y) (y) (y) (y), the number 4 is the EXPONENT.

exponential equation \ˌek-spə-'nen-chəl i-'kwā-zhən\
MATHEMATICS. An equation in which a variable or unknown quantity is used as an exponent.

In the EXPONENTIAL EQUATION *$3^x=9$, the value of x is 2.*



extensor muscle \ik-'sten(t)-sər 'məs-əl\
ANATOMY. A muscle that straightens or extends a part of the body, such as an arm or a leg.

The deltoid muscle of the shoulder is an EXTENSOR MUSCLE *that raises the arm.*

exterior angle \ek-'stir-ē-ər 'aŋ-gəl\
MATHEMATICS. The angle between any one side of a polygon and an adjacent side extended; also, one of the four outside angles formed by a transversal cutting across two coplanar lines.

Any EXTERIOR ANGLE *of a triangle is equal to the sum of the two nonadjacent interior angles.*

exterior system \ek-'stir-ē-ər 'sis-təm\

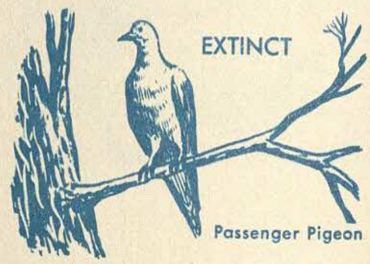
ASTRONOMY. Any galaxy other than the galactic system of the earth.

An EXTERIOR SYSTEM *is called exterior because it is outside our galaxy, the Milky Way.*

extinct \ik-'stiŋ(k)t\ *adj.*

BIOLOGY. Referring to a species or larger group that is no longer living.

The passenger pigeon is an EXTINCT *bird.*



extract \ik-'strakt\ *v.*

1. CHEMISTRY. To remove by distilling, evaporating or by applying a solvent. 2. MATHEMATICS. To calculate the root of a number or quantity. 3. To remove forcibly, with effort.

Commercial firms EXTRACT *water from milk to make powdered milk.*

extragalactic nebula \ˌek-strə-gə-'lak-tik 'neb-yə-lə\

ASTRONOMY. A nebula beyond the earth's galactic system.

The Great Nebula in Andromeda is an EXTRAGALACTIC NEBULA *visible to the naked eye.*

extrapolation \ik-ˌstrap-ə-'lā-shən\ *n.*

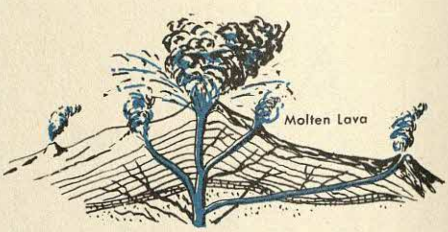
MATHEMATICS. The process of applying relationships taken from observed data to instances not observed; also, the process of using data within a given domain of a function to determine values of the function at points beyond the given domain.

It is possible to estimate the population increase of a future date by EXTRAPOLATION *of population trends.*

extrusive \ik-'strü-siv\ *adj.*

EARTH SCIENCE. Referring to an igneous eruption or flow through the earth's surface.

A hardened mass of lava is an EXTRUSIVE *rock.*



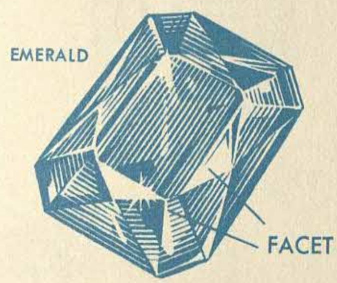
EXTRUSIVE

eye \'ī\ *n.*

1. ANATOMY and ZOOLOGY. In human beings and other animals, the complex organ of sight that changes light into nerve impulses. 2. BOTANY. The core or center of a flower or plant; also, the bud of a tuber. 3. EARTH SCIENCE. The relatively calm area at the center of a hurricane.

The human EYE *is sensitive to a wide range of light intensities and hues.*

F



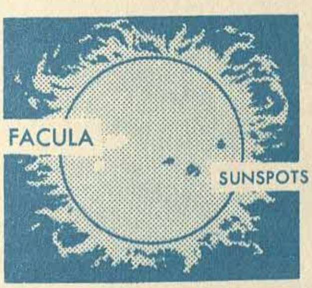
°F.

An abbreviation for a temperature measured on the Fahrenheit temperature scale. See *Fahrenheit temperature scale.*

face \'fās\ *n.*

1. MATHEMATICS. One of the plane surfaces that form a polyhedron, a dihedral angle or a polyhedral angle. 2. EARTH SCIENCE. An open rock surface that shows the rock or mineral layers or that shows where work is progressing, as a cliff, the end of a tunnel, a drift or an excavation; also, one of the flat surfaces of a crystal.

One FACE *of a pyramid is a polygon, and the other faces are triangles.*



facet \'fas-ət\ *n.*

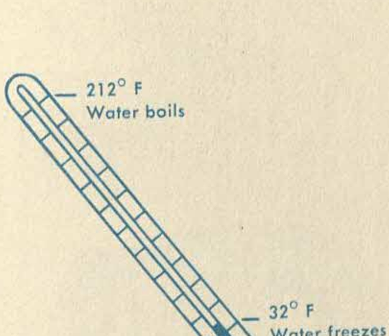
1. EARTH SCIENCE. Any of the faces of a gemstone; also, an abraded (worn) surface of a rock. 2. ZOOLOGY. One of the many small surfaces that make up the compound eye of certain insects. 3. ANATOMY. A small, smooth surface on a bone or other hard part.

A FACET *of a diamond is one of the natural cleavage planes of the crystal.*

factor \'fak-tər\ *n.*

1. MATHEMATICS. One of two or more integers or expressions that have a product equal to the given integer or expression; also, the divisor of an expression. 2. BIOLOGY. A gene or a determiner of a certain hereditary characteristic.

One FACTOR *of* $(x^2 - y^2)$ *is* $(x - y)$, *and the other is* $(x + y)$.



FAHRENHEIT TEMPERATURE SCALE

facula \'fak-yə-lə\ *n.*

ASTRONOMY. A spot on the surface of the sun that appears brighter than the surrounding area as opposed to a sunspot, which is darker than the surrounding area.

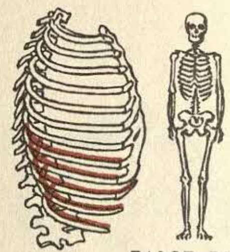
A FACULA *is most easily seen against the less-bright or less-luminous background near the sun's edge.*

Fahrenheit temperature scale \'far-ən-ˌhīt 'tem-pər-ˌchü(ə)r 'skāl\

CHEMISTRY and PHYSICS. The thermometer scale developed by

Gabriel D. Fahrenheit. Under conditions of standard atmospheric pressure, the boiling point of water is 212°, and the freezing point is 32° above the zero point on this scale. The zero point is approximately equal to the temperature of a mixture of equal amounts, by weight, of snow and salt ($NaCl$). Abbreviation for a given point on the scale is F.

To convert a temperature expressed in degrees Centigrade to the FAHRENHEIT TEMPERATURE SCALE, *multiply by 9/5 and add 32 (F. = 9/5 C. + 32).*



FALSE RIBS

fallout \\'fȯ-ˌlau̇t\\ *n.*

PHYSICS. Radioactive particles in the atmosphere that result from a nuclear explosion; also, the falling of radioactive particles through the atmosphere.

FALLOUT *may be absorbed in cloud formations and may cause radioactive rain.*

falls \\'fȯlz\\ *n.*

EARTH SCIENCE. The flow of water over a steep slope or over a vertical separation in a stream bed; also called waterfall, cascade or cataract.

One cause of a FALLS *is the varying erosion resistance of rock formations in a stream bed.*

FAMILY

false ribs \\'fȯls 'ribz\\

ANATOMY. The five pairs of lower ribs in the human skeleton.

The FALSE RIBS *are attached to the spinal column like other ribs, but they are not connected directly to the breastbone.*

family \\'fam-(ə-)lē\\ *n.*

1. BIOLOGY. A grouping, or ranking, above a genus and below an order in the classification of plants and animals. 2. CHEMISTRY. A group of chemical elements that have similar properties, such as the same number of electrons in the outermost shell. 3. MATHEMATICS. A set of lines or surfaces that have a common geometric property.

The name of each animal FAMILY *contains the suffix –idae, while all plant families contain the suffix –aceae.*

fang \\'faŋ\\ *n.*

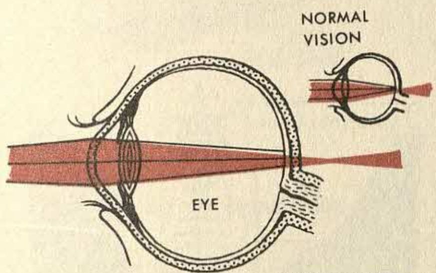
ZOOLOGY. One of the long, curved, hollow, venom-ejecting teeth located in the front part of the jaw of poisonous snakes; also, one of the four long, pointed teeth that meat-eating animals use to seize and tear prey; also called canine tooth.

A snake's FANG *lies against the roof of its mouth when the mouth is closed.*

farad \'far-ˌad\ *n.*

PHYSICS. A unit of electrical capacity equal to the capacitance of a capacitor (condenser) between whose plates there is a potential of one volt when the capacitor is charged with one coulomb of electricity.

Because the FARAD *is a measuring unit too large for most practical purposes, the microfarad is more commonly used.*



FARSIGHTED

faraday \'far-ə-ˌdā\ *n.*

PHYSICS. A measurement of electricity equal to 96,500 coulombs, or the amount of electricity carried by electrolysis per gram-equivalent weight of the ions of the substance.

The FARADAY *of electricity is based only on the mass of the substance deposited on, or liberated at, an electrode, not on the time used for the passage of the current.*

Faraday's laws \'far-ə-dāz 'lȯz\

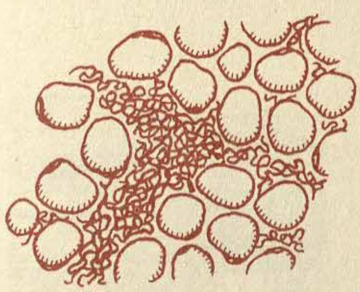
CHEMISTRY. Laws of electrolysis stating that (*a*) The amount of chemical decomposition in an electrolytic cell is in direct proportion to the amount of electricity passed through the cell. (*b*) The amounts of different substances that are deposited or dissolved by the same amount of electricity are in direct proportion to their equivalent weights.

Evidence supporting FARADAY'S LAWS *is found in the electrical nature of matter.*

farsighted \'fär-'sīt-əd\ *adj.*

PHYSIOLOGY. Referring to a condition of the eye in which distant objects are seen more clearly than objects at close range because the images of objects near the eye come to a focus behind the retina. Farsightedness is caused either by loss of elasticity of the lens or by shortness of the eyeball from front to back.

To help correct FARSIGHTED *vision, glasses with convex lenses are used to make the images of nearby objects focus on the retina.*


FAT
(TISSUE CELLS)

fat \'fat\ *n.*

1. BIOLOGY. A greasy solid or liquid found in the tissues of animals and certain plants. Beef suet, lard, olive oil and peanut oil are examples. 2. CHEMISTRY. An ester formed by the reaction of glycerol, $C_3H_5(OH)_3$, with an organic acid of high molecular weight, such as oleic acid, $C_{17}H_{35}COOH$, or palmitic acid, $C_{15}H_{31}COOH$. It is insoluble in water, colorless, odorless and tasteless.

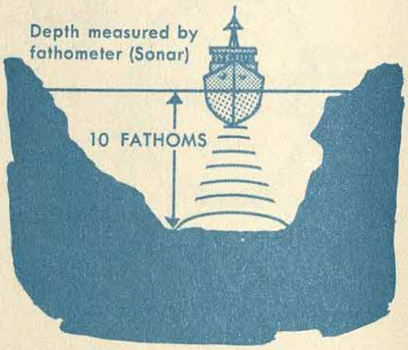
FAT *is an energy-yielding food.*

fathom \'fa<u>th</u>-əm\ *n.*

EARTH SCIENCE and MATHEMATICS. A unit that is equivalent to 6 feet, or 1.83 meters, commonly used for measuring water depths.

The FATHOM *is the unit frequently used in measuring the depths of river and bay channels.*

FATHOM



fatigue \fə-'tēg\ *n.*

1. PHYSIOLOGY and ZOOLOGY. A temporary reduction of the ability of an organism or of its parts to function efficiently after prolonged or excessive exertion or overstimulation; a state of weariness or exhaustion. 2. CHEMISTRY. The tendency of solids, especially metals, to break under stress that exceeds their tensile strength.

An inadequate supply of oxygen during exercise will increase muscular FATIGUE.

fatty acids \'fat-ē 'as-ədz\

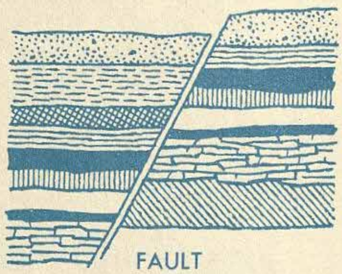
CHEMISTRY. A general name for a group of organic acids that, combined with glycerol, forms compounds classified as esters. The most common fatty acids are oleic, palmitic and stearic acid, all of which are waxy and fatty in appearance; see *fat* (2).

FATTY ACIDS *play an important role in the manufacture of soap.*

fault \'fȯlt\ *n.*

EARTH SCIENCE. A crack or separation in rock formations with vertical, horizontal, or vertical and horizontal, movement of the two sides relative to each other; see *normal fault, reverse fault, thrust fault* and *gravity fault.*

A FAULT *is caused by movement of the earth's crust.*



FAULT

fauna \'fȯn-ə\ *n.*

ZOOLOGY. The animals found in a specific region or time; also, a listing and description of all the animals of an area or region; contrasted to flora.

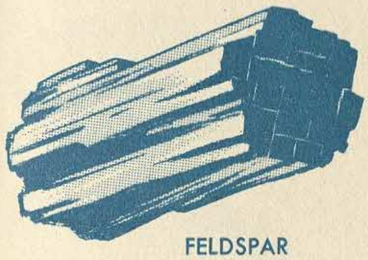
FAUNA *that live in desert areas have developed characteristics different from those of animals that live in polar regions.*

feedback \'fēd-ˌbak\ *n.*

1. ENGINEERING. The process in which some of the energy from the output circuit of an amplifier is transferred back into the amplifier's input circuit. 2. The return of part of the output to the input phase of a process, machine or biological system.

The squeal sometimes produced by a public address system is

an example of FEEDBACK *caused when the microphone is placed too near the loudspeaker.*

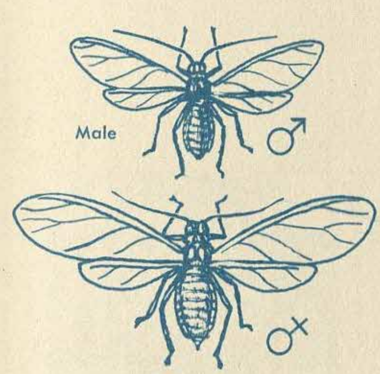


FELDSPAR

feldspar \'fel(d)-ˌspär\ *n.*
EARTH SCIENCE. Any of an abundant group of rock-forming minerals that contains silica, oxygen, aluminum and varying amounts of other minerals. Feldspars weather to form clay minerals.

FELDSPAR *is one of the principal minerals in granite and basalt rocks.*

SPRING GRAIN APHID



FEMALE

female \'fē-ˌmāl\ *adj.*
1. ZOOLOGY Referring to the sex, or to the characteristics of that sex, that bears offspring. 2. BOTANY. Pertaining to a plant, or to organs of a plant, that requires fertilization; pistillate; see *pistil.*

In certain species, the FEMALE *animal is often larger than the male.*

fermentation \ˌfər-mən-'tā-shən\ *n.*
CHEMISTRY. A chemical reaction that changes sugar into alcohol.

Enzymes, which are complex compounds, aid in the FERMENTATION *of sugar solutions, such as fruit juices.*

FERMENTATION

$$C_6H_{12}O_6 \xrightarrow{\text{ZYMASE}} 2C_2HO_5H + 2CO_2$$

ferrite \'fe(ə)r-ˌīt\ *n.*
CHEMISTRY. Any one of a number of ceramiclike chemical compounds containing ferric oxide, Fe_2O_3. Most are magnetic and have the crystalline structure of spinel. High permeability and electrical resistivity make them useful in transformers and other electronic devices.

Components made of FERRITE *are used in radio antennas, TV picture tubes and in digital computer systems.*

ferroalloys \ˌfer-ō-'al-ˌȯiz\ *n.*
CHEMISTRY. Alloys of iron with such other metals as silicon, manganese, tungsten or chromium.

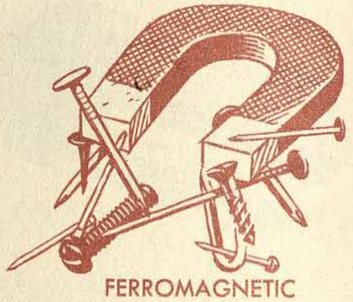
FERROALLOYS *are sometimes used to deoxidize molten steel.*

ferromagnesian \ˌfer-ō-ˌmag-'nē-shən\ *adj.*
EARTH SCIENCE. Referring to any of the silicate minerals that contains iron and magnesium, such as olivine, augite, hornblende and biotite.

Rocks containing FERROMAGNESIAN *minerals are dark in color and have a high specific gravity.*

ferromagnetic \\ˌfer-ō-ˌmag-ˈnet-ik\\ *adj.*
EARTH SCIENCE and PHYSICS. Referring to any substance that can be attracted to a magnetic body, such as iron, nickel, cobalt and gadolinium; also, referring to a substance with magnetic properties, such as magnetite.

A FERROMAGNETIC *substance can be magnetized by stroking it with a permanent magnet or by placing it in a coil of wire that is carrying an electric current.*


FERROMAGNETIC

ferrous \\ˈfer-əs\\ *adj.*
CHEMISTRY. Referring to chemical compounds or ions of iron in which the iron shows an oxidation state, or valence, of +2.

FERROUS *sulfate, used in the manufacture of ink, is combined with tannic acid to form ferric tannate, a black coloring substance.*

ferrous alloys \\ˈfer-əs ˈal-ȯiz\\
CHEMISTRY. Another term for ferroalloys. See *ferroalloys.*

fertilization \\ˌfərt-ᵊl-ə-ˈzā-shən\\ *n.*
BIOLOGY. The union of the egg cell of a female plant or animal with the sperm cell of a male plant or animal.

FERTILIZATION *can occur only in a mature egg cell.*

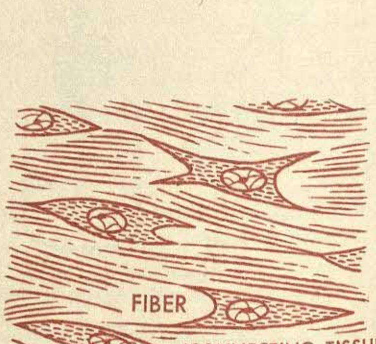

FETUS

fetus \\ˈfēt-əs\\ *n.*
ANATOMY and ZOOLOGY. An unborn offspring that has developed the characteristics of the species to which it belongs. It usually applies to the later stages of the embryos of vertebrate animals.

In man, the embryo is called a FETUS *after the end of the eighth week of development.*

F_1 generation \\ˈef-ˌwən ˌjen-ər-ˈā-shən\\
BIOLOGY. The offspring of an organism, or organisms, taken as a starting point; the first filial generation.

In a monohybrid cross, the F_1 GENERATION *resembles one of the parents one-half of the time.*



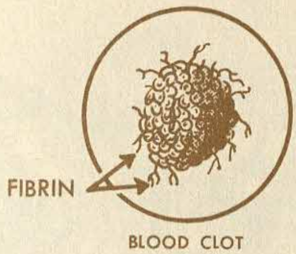
fiber \\ˈfī-bər\\ *n.*
BIOLOGY. A strand, or filament, of protoplasmic material produced by cells but located outside the cells.

The cotton plant produces a FIBER *that is valuable to man.*

fibrin \\ˈfī-brən\\ *n.*
PHYSIOLOGY. An insoluble, elastic protein that is formed by a

chemical reaction when blood clots. It becomes a network of small fibers.

FIBRIN *is formed from fibrinogen, a blood plasma protein.*



fibrous roots \'fī-brəs 'rüts\

BOTANY. Roots that are slender and fiberlike; also, roots of the second order, branched repeatedly, with no root more prominent than another.

Wheat, oats, rye, corn, sorghum and rice have FIBROUS ROOTS.

fibrovascular \ˌfī-brō-'vas-kyə-lər\ *adj.*

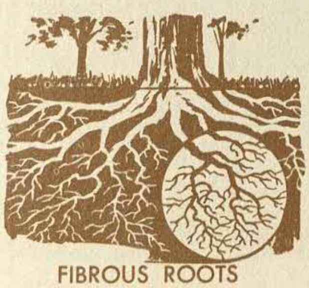
BIOLOGY. Having conducting tissue that consists of conducting cells, or vessels, and fibers.

In plants such as corn, buttercups and oak trees, the FIBROVASCULAR *bundles consist of fiber, phloem and xylem cells.*

fidelity \fə-'del-ət-ē\ *n.*

PHYSICS. The degree to which a sound system, such as a radio or phonograph, reproduces the original signal fed into it.

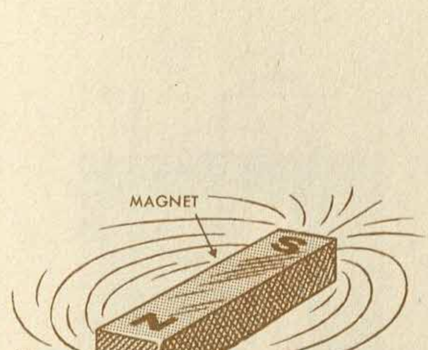
FIDELITY *is accomplished by designing the parts of a system so that the wave form of the input signal is not changed.*



field \'fēld\ *n.*

1. PHYSICS. The space in which a force such as magnetism has influence; also, the area visible through an instrument such as a telescope. 2. MATHEMATICS. A set of elements for which two operations, addition and multiplication, are defined and for which the following conditions hold: (*a*) The set forms a commutative group with respect to addition. (*b*) The set of nonzero elements forms a commutative group with respect to multiplication. (*c*) Multiplication is distributive over addition; that is, if a, b and c are elements of the set, then $a \times (b + c) = a \times b + a \times c$.

Tides are evidence that the earth is within the gravitational FIELD *of the moon.*



field magnet \'fēld 'mag-nət\

ENGINEERING. A magnet that produces the magnetic field in certain machines, such as electric motors and generators.

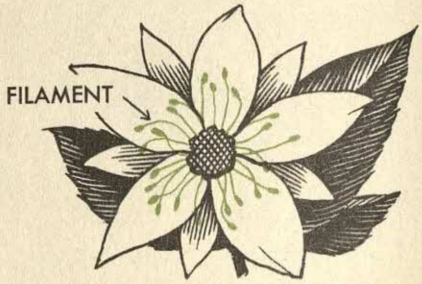
The FIELD MAGNET *of a small electric motor, such as those found in toys and model airplanes, usually is a permanent magnet.*

filament \'fil-ə-mənt\ *n.*

1. BOTANY. The stalk of the stamen that bears the anther at its tip; also, a row of slender cells found in certain algae. 2. PHYSICS.

The wire in a bulb or a vacuum tube that gives off light and electrons when heated.

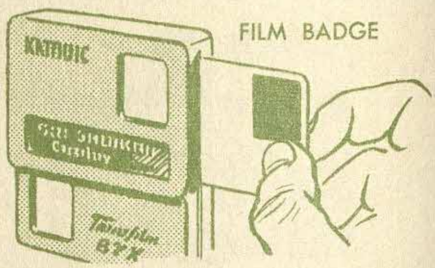
Each stamen has a slender stalk, or FILAMENT, *at the top of which is an anther, the pollen-bearing organ.*



filial generation \'fil-ē-əl ˌjen-ər-'ā-shən\
BIOLOGY. The F_1 generation. See *F_1 generation.*

film badge \'film 'baj\
PHYSICS. A metal, plastic or paper device containing film packets. When developed, the film indicates the amount of ionizing radiation to which it was exposed. A film badge can be attached to the clothing or made into a ring or bracelet.

The FILM BADGE *has helped to create safer working conditions for scientists and technicians who work with radioactive materials.*

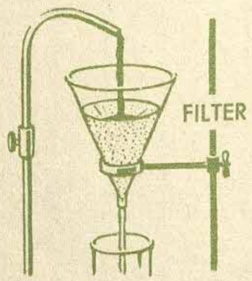


filter \'fil-tər\ *n.*
1. CHEMISTRY. Any porous material, such as cloth, paper, charcoal or sand, that is used to separate a liquid from the solids contained in it. 2. PHYSICS. A device that allows a selected range of frequencies of energy, such as light, sound and electricity, to pass through and that suppresses other frequencies not within this range.

In a laboratory, a paper FILTER *is placed in a glass funnel to remove the suspended particles from a liquid that is poured through it.*

filterable virus \'fil-t(ə-)rə-bəl 'vī-rəs\
MEDICINE. An organism so small that it passes through a fine bacteria-retaining filter. Some cause diseases such as mumps, smallpox, measles and poliomyelitis.

A FILTERABLE VIRUS, *like any other virus, is unable to grow and reproduce itself outside the living protoplasm of its host.*



filtrate \'fil-ˌtrāt\ *n.*
CHEMISTRY. The liquid that is collected after a filter has removed the solid particles in the liquid.

Dissolved chemical substances are often present in a FILTRATE.

fin \'fin\ *n.*
1. ZOOLOGY. A winglike organ on the bodies of fish and certain other animals that live in the water. Fins are used in swimming, turning and balancing. 2. AERONAUTICS and ASTRONAUTICS.

A fixed or adjustable airfoil attached to an aircraft or rocket and used to provide directional stability.

A FIN *is composed of a web of skin supported by horny rays, or rods.*


FIN

finite \'fī-ˌnīt\ *adj.*

MATHEMATICS. Having a limit or being bounded, as numbers that can be reached by counting and quantities neither so large nor so small that they cannot be measured. A set is finite if the number of its elements is zero or some positive integer.

The letters of the English alphabet constitute a FINITE *set.*

fireball \'fī(ə)r-ˌbȯl\ *n.*

1. ASTRONOMY. An unusually bright meteor; see *bolide.* 2. PHYSICS. The cloud of dust and water vapor created by a nuclear explosion.

A FIREBALL *may be bright enough to be visible during the daytime.*


FIREBALL

firedamp \'fī(ə)r-ˌdamp\ *n.*

CHEMISTRY. A highly-explosive mixture of methane and air found in the seams of coal mines.

FIREDAMP *is frequently the cause of explosions in coal mines.*

firn \'fi(ə)rn\ *n.*

EARTH SCIENCE. Granular snow that is partly compacted by alternating freezing and thawing action. It is commonly found on high mountains and is also called névé.

On mountain glaciers, the FIRN *has an average thickness of 100 feet before it recrystallizes into glacial ice.*

first-quarter moon \'fərst-ˌkwȯ(r)t-ər 'mün\

ASTRONOMY. The phase of the moon occurring midway between a new moon and a full moon; as viewed from the earth, the phase when the right half of the moon's surface is illuminated by the sun's light.

A FIRST-QUARTER MOON *is at the observer's meridian at approximately 6:00 P.M.*

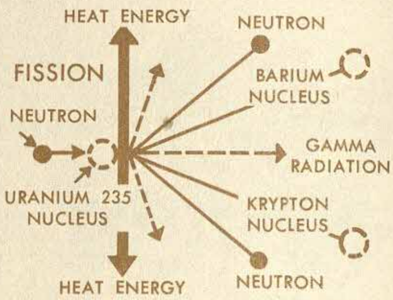

FIRST-QUARTER MOON

fission \'fish-ən\ *n.*

1. CHEMISTRY and PHYSICS. The splitting of the nucleus of an atom into two or more parts of about equal size, accompanied by the release of large amounts of energy. 2. BIOLOGY. An asex-

ual method of reproduction by which a single cell divides into two or more parts that are approximately equal in size.

The discovery in 1931 of the process of FISSION *led to the atomic bomb.*



fissure \'fish-ər\ *n.*

EARTH SCIENCE. A narrow opening in a rock or rock formation caused by tension or pressure that pulls the rock apart.

Although relatively narrow, a FISSURE *usually has an extensive length.*

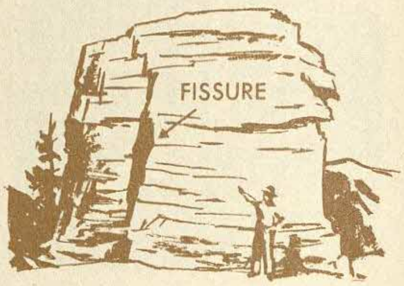
fistula \'fis(h)-chə-lə\ *n.*

MEDICINE. An abnormal passage that leads from an abscess, or from any hollow organ, to a free surface.

The surgical removal of a FISTULA *is called a fistulectomy.*

fix \'fiks\

1. CHEMISTRY (V.). To combine free nitrogen with other elements to form compounds; also, to remove chemically from an exposed photographic film those substances that are sensitive to light. 2. BIOLOGY (V.). To kill, harden and preserve organisms or fresh tissue for microscopic study or other purposes; also, to establish or make permanent by selective breeding. 3. AERONAUTICS (N.). The position of an aircraft as determined by reference to celestial objects, landmarks or by the use of electronic aids.



Discharges of lightning in the atmosphere FIX *nitrogen compounds in the form of oxides that, when dissolved in rainwater, become available for plant nourishment.*

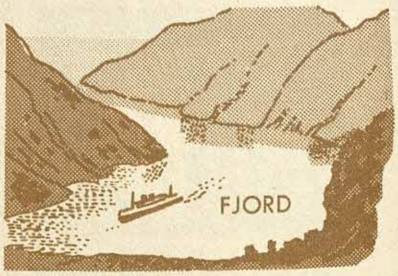
fixed star \'fikst 'stär\

ASTRONOMY. A star whose apparent motion, relative to surrounding stars, does not change over long periods of time.

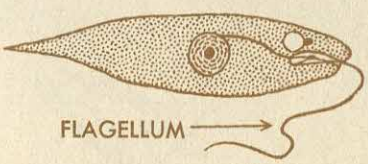
A FIXED STAR *is so distant from the earth that its movements are difficult to detect.*

fjord \fē-'ȯ(ə)rd\ *n.*

EARTH SCIENCE. A long, narrow, very deep bay with steep sides and a U-shaped cross section. A fjord is formed by the thick ice of a valley glacier that has scooped out a valley below sea level. Fjords are responsible for the irregular coastlines of Norway, Alaska and Greenland; also spelled fiord.



A FJORD *is a stream valley that has been deepened and broadened by a glacier and then partially filled by the sea when the glacier melted.*



flagellum \flə-'jel-əm\ *n.*

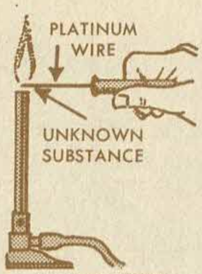
BIOLOGY. A long whiplike extension of the cytoplasm of bacteria, protozoa and certain plant and animal cells, used as an organ of locomotion or circulation.

The euglena is able to move about by means of a FLAGELLUM.

flame test \'flām 'test\

CHEMISTRY. A method used to identify certain elements, such as sodium or potassium, or compounds of such elements, by the color given to a colorless flame in which the unknown substance is heated.

The characteristic color of the flame in the FLAME TEST *for an element is a result of the excitation by heat of the orbiting electrons in the atoms.*



flammable \'flam-ə-bəl\ *adj.*

CHEMISTRY. Pertaining to any substance that is easily set on fire; used interchangeably with inflammable.

*Gasoline is a dangerously-*FLAMMABLE *substance.*

flares \'fla(ə)rz\ *n.*

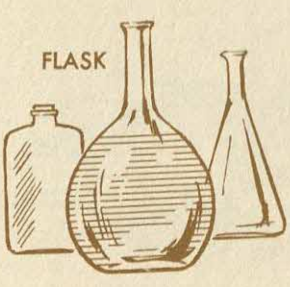
ASTRONOMY. Outbursts of energy on the sun that are part of large and active sunspot groups. Flares usually rise to a great intensity in a few minutes and fade slowly.

Because FLARES *on the sun affect the magnetic field surrounding the earth, they produce disturbances in radio transmission and reception.*

flash flood \'flash 'fləd\

EARTH SCIENCE. A sudden onrush of water down a canyon or a valley following a cloudburst or heavy rain on nearby higher ground.

A FLASH FLOOD *in an arid or semiarid area may be the principal agent of erosion.*



flash point \'flash 'pȯint\

CHEMISTRY. The lowest temperature at which the vapor from a flammable substance will burst into flame.

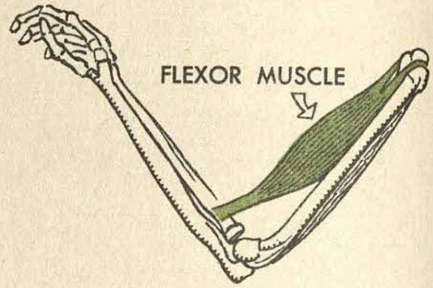
The FLASH POINT *test is valuable in formulating fire and safety rules.*

flask \'flask\ *n.*

CHEMISTRY. A container, generally of glass, used to hold liquids, and sometimes other substances, for laboratory work. It is

formed with a neck for pouring and for the reception of stoppers.

A FLASK *with a graduated neck is often used for the accurate measurement of liquids.*



F layer \'ef 'lā-ər\

EARTH SCIENCE. A layer of concentrated ionization in the ionosphere between altitudes of 100 and 300 miles.

The F LAYER *exists in the daytime as two layers, the* F_1 *and the* F_2 *layers.*

flexor muscle \'flek-sər 'məs-əl\

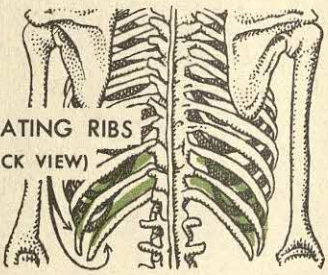
ANATOMY and ZOOLOGY. A muscle that bends a limb or other part of an animal's body. The bending takes place at a joint, such as at the elbow or knee in man.

When a FLEXOR MUSCLE *contracts, an extensor muscle relaxes.*

flight path \'flīt 'path\

AERONAUTICS and ASTRONAUTICS. The path that an aircraft, rocket or projectile takes through the atmosphere or space.

A planned FLIGHT PATH *in the atmosphere is sometimes altered by changes in wind velocity and direction.*



floating-card compass \'flōt-iŋ-ˌkärd 'kəm-pəs\

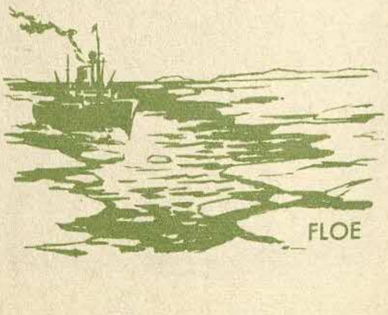
PHYSICS. An instrument that consists of a steel magnet suspended in a liquid so it can turn easily in a horizontal plane to set itself along a magnetic north and south line.

The Chinese invented the FLOATING-CARD COMPASS *and used a lodestone as a magnet.*

floating ribs \'flōt-iŋ 'ribz\

ANATOMY. The two lowest pairs of ribs. They are attached to the vertebrae in the back but not to the breastbone (sternum) or the cartilage of other ribs.

In man, the FLOATING RIBS *make up the eleventh and twelfth pairs of ribs.*



flocculent \'fläk-yə-lənt\ *adj.*

ZOOLOGY. Referring to something covered with a waxy, woollike substance.

The FLOCCULENT *sheath of some scale insects gives protection for the female and her eggs.*

floe \'flō\ *n.*

EARTH SCIENCE. A mass or field of floating sea ice that appears

after a summer breakup of ice in the Arctic or Antarctic regions. A floe is usually frozen to a depth of eight to ten feet below the water.

A FLOE *originating in the Arctic Ocean is composed of salt-water ice that has a freezing point below 32° F.*

flood plain \'fləd 'plān\

EARTH SCIENCE. A stretch of nearly-level land bordering a stream or river and composed of sediment deposited during floods.

The sediment of a FLOOD PLAIN *is deposited by slow-moving water that has left the main stream channel.*

flora \'flōr-ə\ *n.*

BOTANY. The plant life of a particular region or period; also, a listing and description of all the plants of an area or region; contrasted to fauna.

The study of ecology is concerned with the relationships and interactions of FLORA *and fauna and their environment.*

florescence \flō-'res-ᵊn(t)s\ *n.*

BOTANY. The act of flowering or the state of being in bloom.

A rapid FLORESCENCE *often occurs on the desert after a spring rain.*

floriculture \'flōr-ə-,kəl-chər\ *n.*

BOTANY. The branch of horticulture concerned with the management and cultivation of flowering plants and ornamental shrubs and trees, usually on a commercial scale.

An understanding of the temperature, light and soil requirements of plants is necessary for successful FLORICULTURE.

flotation process \flō-'tā-shən 'präs-,es\

CHEMISTRY and EARTH SCIENCE. A method used to separate minerals from their ores by mixing the pulverized ore with an oil-water mixture and whipping the mixture into a foam or froth. The mineral then becomes coated with oil, floats and can be floated off and purified.

The FLOTATION PROCESS *makes possible the economic recovery of minerals from low-grade ores.*

flower \'flau̇(-ə)r\ *n.*

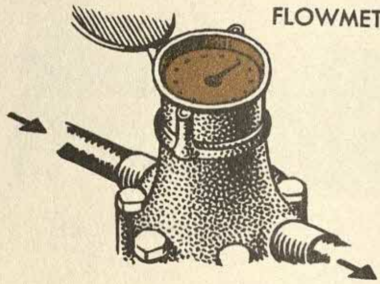
BOTANY. The part of a plant containing, or consisting of, the reproductive organs; a blossom.

The FLOWER *of a grass generally grows in a head or spike.*

flowmeter\'flō-,mēt-ər\ *n.*

ENGINEERING. A device that measures the rate of flow of a fluid. It may be calibrated in such units as gallons per second, cubic feet per minute or liters per hour. A flowmeter may utilize mechanical or electrical devices and can be used to measure flow in pipes or open streams.

A FLOWMETER *is used to check the rate at which chlorine is added to water in water-purification plants.*



fluid \'flü-əd\ *adj.*

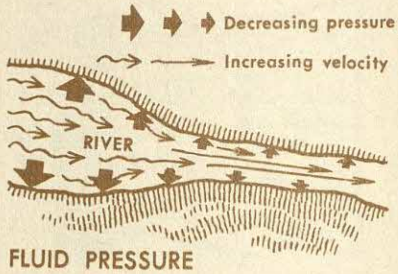
PHYSICS. Referring to the physical state of a substance that can flow.

Hydraulics is a science dealing with FLUID *characteristics.*

fluid pressure \'flü-əd 'presh-ər\

ENGINEERING and PHYSICS. The force per unit area within a fluid, or the force per unit area exerted by a fluid against a surface in contact with it.

When a fluid passes from a wider to a narrower channel, its velocity increases, and the FLUID PRESSURE *on the sides of the channel decreases.*



flume \'flüm\ *n.*

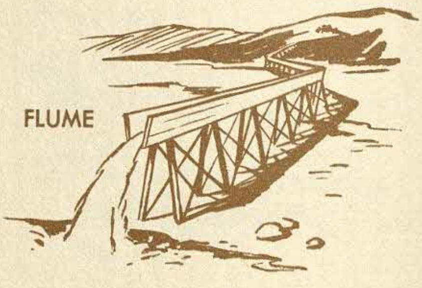
1. ENGINEERING. A trough, or channel, constructed to conduct water from reservoirs or lakes to a distant area. 2. EARTH SCIENCE. A deep, narrow ravine or gorge containing a rapidly-flowing stream.

In mining operations, a FLUME *is often constructed to carry water to, or away from, a mine site.*

fluorescence \(,)flü(-ə)r-'es-^{ə}n(t)s\ *n.*

PHYSICS. The phenomenon characteristic of certain substances by which radiation is absorbed, and different radiation is given off. The phenomenon continues only so long as radiation is being absorbed. When the absorbed radiation is electromagnetic, the radiation given off is always of a longer wavelength.

The fluorescent lamp illustrates FLUORESCENCE *when ultraviolet light produced within the tube is absorbed by the inner coating on the glass and causes emission of visible light.*



fluoridation \,flu̇r-ə-'dā-shən\ *n.*

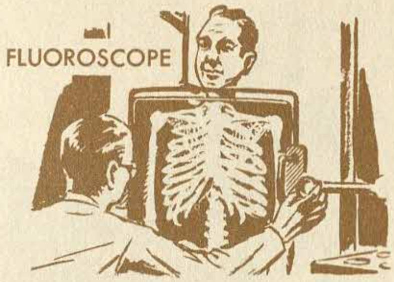
CHEMISTRY and MEDICINE. The process of treating a substance such as water with fluorides; especially, the addition of small quantities of fluorides to a public water supply.

FLUORIDATION *of drinking water has been shown to reduce the incidence of tooth decay.*

fluorocarbons \\ˌflü(-ə)r-ō-ˈkär-bənz) *n.*

CHEMISTRY. A group of compounds composed of carbon and fluorine only. They are usually considered as derivatives of hydrocarbons in which the hydrogen atoms have been replaced by fluorine atoms.

FLUOROCARBONS *are unusually resistant to attack by the most corrosive chemicals.*



fluoroscope \\ˈflu̇r-ə-ˌskōp\\ *n.*

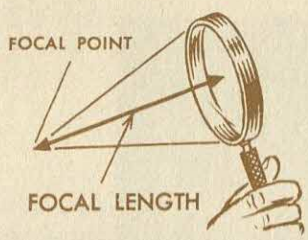
MEDICINE. An X-ray device that shows the shadows of the internal structures of the body on a fluorescent screen.

The FLUOROSCOPE *is of value in diagnosing some internal injuries or disorders and in detecting broken bones.*

flux \\ˈfləks\\ *n.*

1. CHEMISTRY. A substance that is used as an aid in fusing substances and in melting another substance. 2. PHYSICS. The amount of matter, energy, force or power that passes through a specified area in a given time.

Many types of solder contain a FLUX *in a hollow core.*



FM

An abbreviation for frequency modulation. See *frequency modulation.*

focal length \\ˈfō-kəl ˈleŋ(k)th\\

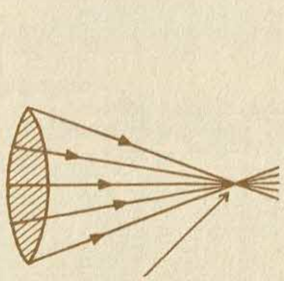
PHYSICS. The distance from the optical center of a lens or a curved mirror to the principal focus.

The FOCAL LENGTH *of California's 200-inch Mt. Palomar telescope mirror is 55½ feet.*

focal plane \\ˈfō-kəl ˈplān\\

PHYSICS. A plane that is parallel to the plane of a lens or a mirror and that is at the proper distance to pass through the focus of the lens.

Many expensive cameras have a shutter at the FOCAL PLANE *to achieve fast shutter speeds, since the shutter thus needs to move a very small distance.*



focal point \\ˈfō-kəl ˈpȯint\\

PHYSICS. The point at which a lens or curved mirror brings together incoming parallel rays of light or other radiation.

The sun's radiation can ignite a piece of paper that is placed at the FOCAL POINT *of a convex lens.*

focus \'fō-kəs\

1. PHYSICS (V.). To move a lens toward or away from an object in order to form a clear image; also, to cause parallel rays of light or other radiation to come together. 2. MATHEMATICS (N.). One of the two fixed points that lies on the major axis, or diameter, of an ellipse and on the transverse axis, or diameter, of a hyperbola and that is used in defining these conics; also, the fixed point on the axis of a parabola that is used in defining the parabola. 3. EARTH SCIENCE (N.). The source, or origin, of earthquake waves.

A noticeable time delay occurs if, when reading a book, one tries to FOCUS *his eyes on a distant object.*

FOEHN

foehn \'fə(r)n\ *n.*

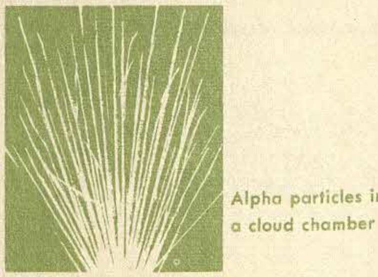
EARTH SCIENCE. A warm, dry wind that blows down the northern slopes of mountains, as the Alps. It is similar to the chinook on the eastern slopes of the Rocky Mountains.

In the western United States, a FOEHN *is often called a snoweater because it quickly melts a great deal of the snow in its path.*

fog \'fȯg\ *n.*

EARTH SCIENCE. A relatively-dense mass of water droplets in the lower atmosphere near the surface of the earth that occurs when warm, humid air passes over a cold area and is cooled to the dew point.

If the air temperature is below freezing, a FOG *may consist of tiny ice needles.*



FOG TRACKS

fog tracks \'fȯg 'traks\

PHYSICS. The paths of electrified particles through a supersaturated vapor, made visible by the formation of trails of microscopic liquid droplets.

Observing FOG TRACKS *in a cloud chamber within a magnetic field makes it possible to detect the type of electrical charge on particles emitted from radioactive materials.*

FOLD

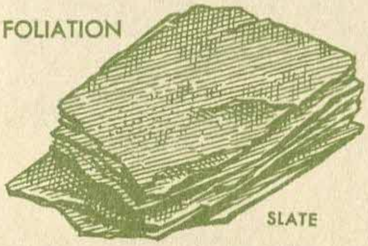
fold \'fōld\ *n.*

EARTH SCIENCE. Rock layers that have been bent or wrinkled into a wavelike formation. Folds are caused by movements in the earth's crust.

A FOLD *may be an inch or less in height or so huge that it forms a mountain range.*

foliage \'fō-l(ē)ij\ *n.*
BOTANY. The whole leaf system of a tree or a plant; leafage.

The symptoms of mineral deficiency in plants can be detected in the FOLIAGE.



foliation \ˌfō-lē-'ā-shən\ *n.*
1. EARTH SCIENCE. The parallel arrangement of minerals in a rock, giving it a layered or leaflike structure; also called slaty cleavage. 2. BOTANY. The leaves of a plant; also, the way leaves are arranged in the bud or on the stem.

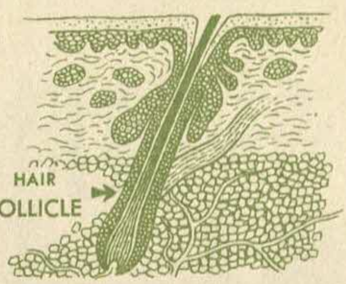
Metamorphic rocks, such as schist and gneiss, show FOLIATION.

follicle \'fäl-i-kəl\ *n.*
ANATOMY and ZOOLOGY. Any small sac or gland that normally secretes or excretes a substance.

Each human hair grows from a FOLLICLE *in the lower layers of the skin.*

follicle-stimulating hormone \'fäl-i-kəl 'stim-yə-ˌlāt-iŋ 'hȯr-ˌmōn\
PHYSIOLOGY. A hormone that comes from the anterior lobe of the pituitary body and that stimulates the growth of Graafian follicles in the female and activates sperm-producing cells in the male; *abbr.* FSH.

A FOLLICLE-STIMULATING HORMONE *is a protein-carbohydrate in composition.*



food chain \'füd 'chān\
BIOLOGY and PHYSIOLOGY. The nutritional relationship that unites organisms of a biological community, as for example a plant that is eaten by an animal that in turn is devoured by a carnivorous animal that, through metabolism or ultimate death, returns the material to the environment as food for plants.

A FOOD CHAIN *may involve a few organisms or many.*

food web \'füd 'web\
ECOLOGY. The system of food circulation and feeding interrelations in an ecological community, whether forest, grassland, lake or sea.

Simple energy pathways called food chains make up a FOOD WEB.

fool's gold \'fülz 'gōld\
CHEMISTRY and EARTH SCIENCE. Another term for pyrite. See *pyrite.*

foot \'fu̇t\ *n.*

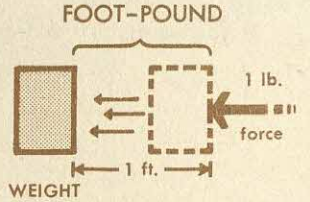
1. MATHEMATICS. A measure of length equal to 12 inches, or ⅓ yard. 2. ANATOMY and ZOOLOGY. The end, or distal part, of the leg on which an organism stands or walks.

The FOOT *is a unit of measure supposedly derived from the length of a man's foot.*

footcandle \'fu̇t-'kan-dᵊl\ *n.*

PHYSICS. A unit of illumination equal to the illumination on a surface that is perpendicular to the rays of light from a one-candlepower source at a distance of one foot.

The photometer is an instrument that can be used to measure intensity of light in units of a FOOTCANDLE.



foot-pound \'fu̇t-'pau̇nd\ *n.*

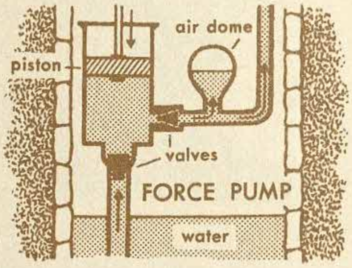
PHYSICS. The unit of work done when a force of one pound moves a body one foot.

In the school science laboratory, the unit of work used may be either the FOOT-POUND *or the dyne-centimeter.*

foot-pound-second system \'fu̇t-'pau̇nd-'sek-ənd 'sis-təm\

PHYSICS. A system of measurement that uses the foot, the pound and the second as the standard units of length, weight and time, respectively. It serves as the basis for many derived units.

The FOOT-POUND-SECOND SYSTEM *is widely used in engineering, but in physics it is being replaced by the meter-kilogram-second system.*



force \'fō(ə)rs\ *n.*

PHYSICS. Any influence on an object that, when unopposed, causes the object to move, change speed or change direction of motion; a pull or push.

A constant unopposed FORCE *will cause a constant acceleration of an object, provided the speed of the object is considerably less than the speed of light.*

force pump \'fō(ə)rs 'pəmp\

ENGINEERING. A pump that moves a fluid by creating a pressure greater than the pressure of the atmosphere.

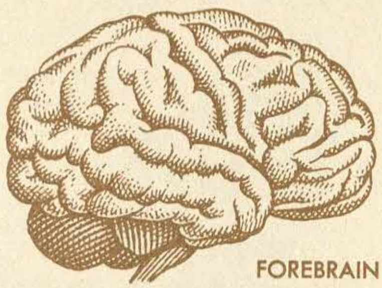
A FORCE PUMP *can raise water higher than 34 feet, which is the limit for pumps using only atmospheric pressure.*

forebrain \'fōr-ˌbrān\ *n.*

ANATOMY. The front part of the developing brain in an embryo;

also, the parts of the mature brain developed from the embryonic structure.

The two halves of the cerebrum make up the major portion of the human FOREBRAIN.



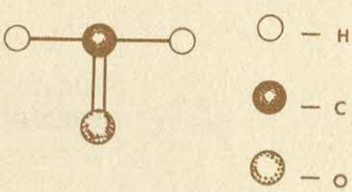
FOREBRAIN

formaldehyde \fȯr-ˈmal-də-ˌhīd\ *n.*
CHEMISTRY. HCHO. A water-soluble gas, the simplest member of the aldehyde compounds, used as an antiseptic and a preservative and in the manufacture of certain plastics.

Formalin, a 40-percent solution of FORMALDEHYDE *in water, is used as a preservative for anatomical specimens.*

formation \fȯr-ˈmā-shən\ *n.*
EARTH SCIENCE. A rock unit composed of the same type of sediment and minerals throughout; also, a stratum of one kind of rock.

A FORMATION *can be distinguished from formations adjacent to it by differences in sediment, minerals and fossils.*



FORMALDEHYDE
(MOLECULAR STRUCTURE)

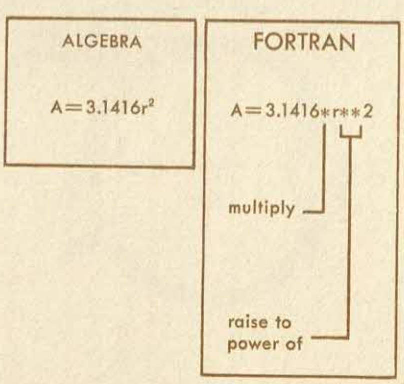
formula \ˈfȯr-myə-lə\ *n.*
1. MATHEMATICS. A statement of a generality or principle by the use of mathematical symbols and notation. 2. CHEMISTRY. An expression representing a chemical compound or the molecule of an element and describing the kinds of atoms (elements) by symbols and the relative number of each kind of atom by subscript numerals. For example, the formula for water is H_2O, designating a compound in which there are two hydrogen (H) atoms for every oxygen (O) atom.

In the FORMULA *for finding the area of a rectangle,* $A = lw$, *l is the length, w is the width and A is the area.*

formulate \ˈfȯr-myə-ˌlāt\ *v.*
To put a plan for action in the form of a systematic statement; also, to prepare a general explanation; also, to put in the form of a formula.

One of the first steps in doing a scientific experiment is to FORMULATE *a plan of procedure.*

(formula for area of circle)



FORTRAN \ˈfȯr-ˌtran\ *n.*
ENGINEERING and MATHEMATICS. A problem-oriented computer language, used for data that can be expressed algebraically; derived from the words, formula translation.

Before a problem written in FORTRAN *can be processed by a computer, it must be translated into machine-oriented language.*

fossil \'fäs-əl\ *n.*

BIOLOGY and EARTH SCIENCE. Animal or plant remains, or a trace of an animal or plant, found naturally preserved in the earth's crust, the preservation having occurred before recorded history.

A FOSSIL *is used by geologists to aid in determining the age of the rock formation in which the fossil is found.*

Foucault pendulum \'fü-ˌkō 'pen-jə-ləm\

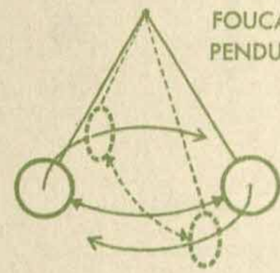
PHYSICS. A swinging mass having little air resistance and supported by a long, thin wire. It demonstrates the rotation of the earth. The mass is set swinging in a plane, and the plane appears to change as the earth rotates.

In the Northern Hemisphere, the plane of a FOUCAULT PENDULUM *appears to rotate in a clockwise direction.*

foundry \'faůn-drē\ *n.*

ENGINEERING. The process of pouring molten metals into shaped molds to make different castings; also, the building in which castings are made.

In a steel FOUNDRY, *molten metal is poured into molds from an electric furnace, a Bessemer converter or an open-hearth furnace.*



fovea \'fō-vē-ə\ *n.*

ANATOMY and ZOOLOGY. A small pit or cuplike depression in a structure of the body; especially, the depression near the center of the retina of the eye.

The FOVEA *in the human eye is the area on the retina where only cones are present and where clearest vision occurs.*

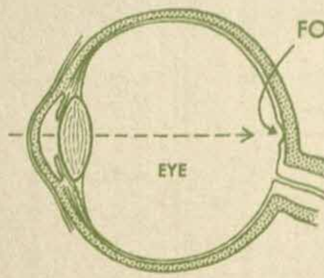
fps

An abbreviation for foot-pound-second. See *foot-pound-second system.*

fraction \'frak-shən\ *n.*

MATHEMATICS. An expression representing the division of one quantity by another quantity.

The expression ⅔ *is a* FRACTION.



fractional distillation \'frak-shnəl ˌdis-tə-'lā-shən\

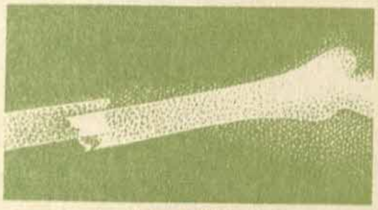
CHEMISTRY. The process by which a mixture of liquids is separated on the basis of the different boiling points of the liquids. Each liquid undergoes heating, vaporization and condensation of the vapor.

Naphtha, kerosene and gasoline are obtained by FRACTIONAL DISTILLATION.

fracture \'frak-chər\ *n.*

1. MEDICINE. A break in a bone or, occasionally, in a cartilage. 2. EARTH SCIENCE. One of the characteristic breakage patterns of a rock or mineral, usually described as *even, uneven, splintery, fibrous, irregular* or *earthy*. Two more technical types of fracture are *hackly* and *conchoidal;* hackly is a jagged-edged fracture, and conchoidal, meaning shell-like, shows concentric arcs.

A bone FRACTURE *may be simple or compound.*



FRACTURE
(X RAY)

fraternal twins \frə-'tərn-əl 'twinz\

Twins who are each produced from separate eggs that usually have been fertilized and have matured at the same time.

FRATERNAL TWINS *may be two boys, two girls, or a boy and a girl, while identical twins are always either two boys or two girls.*

Fraunhofer lines \'fraún-ˌhō-fər 'līnz\

PHYSICS. Dark lines that cross the otherwise-continuous spectrum of sunlight. They are caused by the absorption of certain wavelengths by the sun's or the earth's atmosphere.

Helium was discovered in 1868 through study of the FRAUNHOFER LINES.

free \'frē\ *adj.*

CHEMISTRY. Referring to the uncombined state of an element or radical; not bonded or attached.

Unreactive elements, such as gold, are often found FREE *in nature, while active elements, such as chlorine, are not.*

free energy \'frē 'en-ər-jē\

PHYSICS. That part of the heat content of a system that may be converted into work.

FREE ENERGY *is available in all forms of potential energy, mechanical, electrical and chemical.*

free fall \'frē 'fól\

AERONAUTICS and ASTRONAUTICS. A fall through space or the atmosphere of an object free from restraining or guiding forces; also, a parachutist's drop before his parachute opens.

Since an orbiting space vehicle is in a state of FREE FALL, *zero gravity conditions exist inside the vehicle.*

ABBREVIATIONS

A	ampere
Å	Angstrom unit
abs	absolute
a-c	alternating current (as an adjective)
amu	atomic mass unit
atm	atmosphere
at. wt	atomic weight
AU	astronomical unit
avdp	avoirdupois
Bev	one billion electron volts
bhp	brake horsepower
bhp-hr	brake horsepower-hour
bp	boiling point
Btu	British thermal unit
C	temperature Celsius; temperature Centigrade
c	candle
cal	calorie
cfm	cubic feet per minute
cfs	cubic feet per second
cgs	centimeter-gram-second (system)
cl	centiliter
cm	centimeter
cm^2	square centimeter
cm^3	cubic centimeter
coef	coefficient
colog	cologarithm
cos	cosine
cot	cotangent
cp	candlepower
csc	cosecant
cu	cubic
cu ft	cubic foot
db	decibel
d-c	direct current (as an adjective)
doz	dozen
E	electromotive force
e	the base of the system of natural logarithms
ev	electron volt
F	temperature Fahrenheit
fp	freezing point
fpm	feet per minute
fps	feet per second
ft	foot; feet
ft^2	square foot
ft^3	cubic foot
ft-c	footcandle
ft-lb	foot-pound
G	universal gravitational constant
g	gram
gal	gallon
g-cal	gram-calorie
gpm	gallons per minute
gps	gallons per second
hr	hour
$h\nu$	photon energy
hp	horsepower
Hz	hertz (cycles per second)
I	electric current
ID	inside diameter
in.	inch
in.^{2}	square inch
in.^{3}	cubic inch
in.-lb	inch-pound
ips	inches per second
j	joule
K	temperature Kelvin (absolute)
kcal	kilocalorie
kg	kilogram
kg-cal	kilogram-calorie
kg-m	kilogram-meter
kg/m^3	kilograms per cubic meter
kgps	kilograms per second
km	kilometer
kv	kilovolt
kw	kilowatt
kwhr	kilowatt-hour
l	liter; lumen
lat	latitude
lb	pound
lb-ft	pound-foot
lb/ft^2	pounds per square foot
lb/ft^3	pounds per cubic foot
lb-in.	pound-inch
l-hr	lumen-hour
lin ft	linear foot
log	logarithm (common)
$\log_e$	logarithm (natural)
long.	longitude
m	meter; minute (time, in astronomical circles)
m^2	square meter
m^3	cubic meter
ma	milliampere
Mev	one million electron volts
mg	milligram
mh	millihenry
mi	mile
mi^2	square mile
min	minute
m-kg	meter-kilogram
ml	milliliter
mm	millimeter
mm^2	square millimeter
mm^3	cubic millimeter
$m\mu$	millimicron
mph	miles per hour
mphps	miles per hour per second
mv	millivolt
N	Avogadro's constant
$n!$	factorial n
OD	outside diameter
oz	ounce
pH	rating on acid-alkaline scale
ppm	parts per million
psi	pounds per square inch
psia	pounds per square inch absolute
R	temperature Reaumur; resistance
RA	right ascension
rpm	revolutions per minute
rps	revolutions per second
sec	secant; second
sin	sine
sp gr	specific gravity
sq	square
tan	tangent
V	volt
VA	volt-ampere
W	watt; work
yd	yard
yd^2	square yard
yd^3	cubic yard

SCIENTIFIC SYMBOLS AND ABBREVIATIONS

α	alpha particle
β; β^-	beta particle
β^+	positron
γ	gamma radiation
Δ	a small change; heat
λ	wavelength; radioactive-decay constant
ma	milliampere
μc	microcurie
μf	microfarad
μin.	microinch
μm	micron
$\mu\mu$	micromicron
$\mu\mu$f	micromicrofarad
ν	frequency; neutrino
π	3.14159; osmotic pressure
Σ	the sum of
σ	nuclear cross section (barns); area
Ω	electrical resistance (ohms)
ω	angular speed; angular velocity
$'$	minute (angular measure)
$''$	second (angular measure)
♂	male
♀	female
$>$	is greater than
$<$	is less than
$\propto$	is proportional to
∞	infinity
$\sqrt{\ }$	square root of
$^\circ$	degrees; temperature; angle measurement (example, 30°)
[ ]	molar concentration
$+$	positive electric charge; mixed with; plus
$-$	negative electric charge; single covalent bond; minus
$=$	equals; double covalent bond; produces
$\neq$	does not equal
$\equiv$	triple covalent bond
$\rightarrow$	produces; forms; chemical reaction
$\rightleftarrows$	reversible chemical reaction
$\uparrow$	gas produced by a chemical reaction
$\downarrow$	precipitate produced by a chemical reaction
*	radioactive substance (follows symbol of element; example, Cl*)